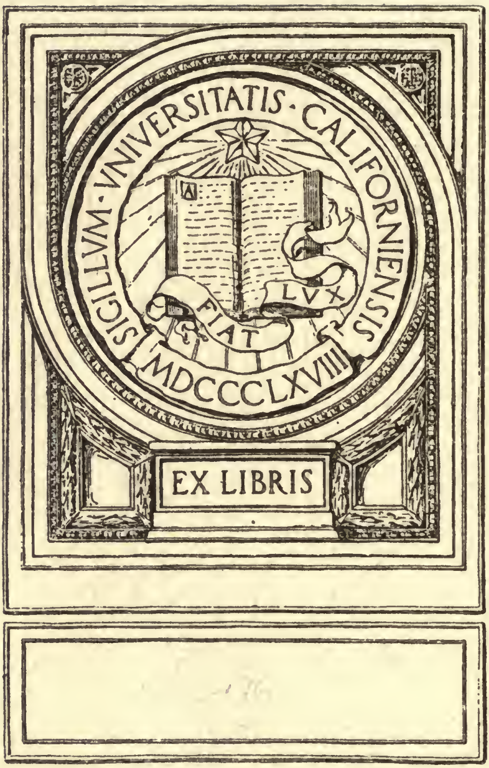
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# The Earth

## Its Life and Death

By

Alphonse Berget
Professor at the Institut Océanographique

Translated by

E. W. Barlow, B.Sc., F.R.A.S.

*Illustrated*



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# PREFACE

EVERYTHING on the surface of our Earth appears to us in living form. Terrestrial or aquatic animals, insects, plants, microscopic organisms—everything is born, lives, and dies. Matter itself is subject to evolution and, under certain conditions, exhibits distinct signs of age and fatigue.

The question arises: Does the Earth, taken as a whole, follow this general law? Does it *live* in a way analogous to that in which all things found on its surface do? These pages have been written to answer this question. I trust that they will give to those who read them a general idea of that science which may be called the physics of the Earth, a science which deserves, in the highest meaning of the word, the beautiful name of Φύσις.

A. B.

LE POULIGUER.

# NOTE

FOR the convenience of English readers, the approximate equivalents of the metric figures are in this volume given also in the more familiar English standards.

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# The Earth: Its Life and Death

## CHAPTER I

### THE BIRTH OF THE EARTH

HOW did the little globe on which we live come into existence in the midst of the universe? Under what circumstances did it originate? What were the causes which determined its constitution, its primæval form? In other words, what were the conditions of its conception and its birth?

These questions, which arise naturally at the beginning of this work, must always have been present to the mind of man. But it is only comparatively recently that sufficient light has been thrown upon them, if not to solve them completely, at any rate to enable us to obtain some idea of the forces which were at work, and the conditions which obtained, during the inception of our Earth, and during its formation as an individual world in the midst of space.

If, on a clear dark night, we look upwards at that expanse which we call the sky, and which seems to be a great dome supported upon the horizon, we see there a wonderful spectacle, which appears, at the first glance, absolutely inextricable. Attentive observation of the heavens has, however, enabled astronomers to classify the phenomena in evidence, and, at the same time, to simplify the difficult problem which constitutes their study.

In the first place, among the innumerable brilliant points which stud the sky, there are some which scintillate and others which shine with a steady light. However great the magnification secured by the telescope utilised, the former appear only as geometrical[1] points; these are the stars which seem to rotate with a continuous movement about an imaginary line passing through a definite point in the heavens. On the other hand, the latter, which are the planets, appear larger with each increase of power of the instruments that we use to study them. Their movements differ from those of the stars; they

[1] Theoretically this is so, but, actually, a star viewed through a telescope shows a disk. This is called "spurious," as it appears merely because of a certain lack of perfection in all lenses. This spurious disk does not increase in size when higher magnifying powers are used.—*Ed.*

revolve around a great and brilliant globe, the Sun.

The Sun itself *appears* to revolve about us, bringing the day when it is visible and leaving us to night when it disappears beneath the horizon, the truth being, however, that it is actually the Earth which moves, turning about its own axis.

A second globe which shines with brilliancy only during the night, and then only at certain times and under variable aspects, is more immediately dependent upon the Earth around which it revolves; this is the Moon.

Other phenomena, also, are exhibited by the celestial bodies. In some places, a large number of very small stars are gathered together so that, while they are all distinct from one another, they form a kind of luminous spot which is called a star-cluster; in other places are seen regions shining with a milky luminosity, distinct from the background of dark sky, having various forms, indefinite, spiral, or circular. These are the nebulæ. An immense whitish track of light traverses and encircles the entire sky; this is called the Milky Way and is an aggregation of a very great number of little stars, of which our Sun doubtless forms one, gigantic for us, microscopic as compared to the immensity of space.

Transitory bodies appear suddenly in the heavens; these are the meteors which resemble fireworks, and which come often in considerable numbers and at fixed epochs; they are called "shooting stars." At certain times, special bodies appear with a luminous nucleus and a long tail. These are comets and their periods are often very long. Occasionally, new stars blaze up suddenly and take on temporarily the appearance of the fixed stars. Their brilliancy increases, remains for a time stationary, and then gradually decreases prior to their disappearance.

These are the simplest observational facts that astronomers have learned. If we now examine the heavenly bodies, not with an ordinary telescope, but with that wonderful apparatus known as the spectroscope, which, by splitting up light into its component rays, enables us to analyse it with great precision, we are able to prove that, at any rate, as far as the Sun and the Earth are concerned, they are composed, for the most part, of the same chemical elements. This fact, alone, is suggestive of their having had a common origin. Some elements which, formerly, were known to exist only in the Sun have since been discovered in the matter of which our Earth is formed.

Our globe, by the character of its movements,

is analogous to the planets, which are all of a spheroidal form and are isolated in space, with a movement of revolution around the Sun. Now, voyages of circumnavigation, in the course of which the sailors have made the entire journey round the Earth, demonstrate to us that it also is isolated in space. Again, the circular form of the shadow which it throws upon the Moon during the eclipses of that body proves its globular form. There is, therefore, one conclusion that we can draw from our preliminary study. The Earth is a planet belonging to the Solar System, constituted of the same elements as the central Sun of that System.

Another piece of information that the spectroscope affords us is that the Sun and the stars are self-luminous bodies, while the planets and the Moon are illuminated bodies which appear bright to us because they reflect the Sun's light and not because they emit light themselves. The self-luminous stars and the Sun must therefore be at a very high temperature, in the midst of celestial space, which the investigations of astrophysicists have shown to be very cold. Just as when the colour of a piece of iron heated in a forge passes, gradually as it cools, from dazzling white to yellow, then to orange, to bright red, and lastly to dull red, we can, from the colour, deduce the tempera-

ture of the iron, so from the colour of a star we can obtain information as to its temperature and age. The blue and white stars are in the height of their period of incandescence. The yellow stars have already cooled to some extent; this is the condition of our Sun. The yellow and orange stars are already on the way towards the period of a more advanced cooling which, after the red phase, leads to the solidification of their surfaces, rendering these obscure and transforming them into extinct suns.

Among the facts observed in the sky and which seem to overwhelm the reason, we must place first that admirable mechanism which maintains the bodies isolated in space and which causes some of them to revolve around others.

This wonderful adjustment was a mystery to man, until Kepler formulated the laws under which the planetary orbits are described and Newton discovered and enunciated the law of universal gravitation, from which Kepler's laws can be deduced mathematically.

Kepler found that the planetary orbits are not exactly circular, but are ellipses of which the Sun occupies one of the foci. This is the first law, from which it follows that the distance from the

centre of the planet to the centre of the Sun, the *radius vector*, to give it its mathematical name, is not a fixed length but varies according to the position of the body in its orbit. Kepler's second law deals with this variation in the length of the radius vector; it states that the area swept over by the radius vector in any given time is always the same, whatever the position of the planet in its orbit. This law governs the velocity with which a planet pursues its path; it moves more rapidly in proportion as it is nearer the Sun, and more slowly in proportion as it is farther from the Sun. The third law governs the time that the planets take to traverse their orbits entirely; the square of the period is proportional to the cube of the major axis of the elliptical orbit in the case of each planet.

From these laws Newton was able to read something more than the principles of the movements that they enunciated. He divined from them the cause of these planetary movements and he gave the great and simple formula determining these in his law of attraction or universal gravitation.

"Any two bodies attract each other with a force directly proportional to the product of their masses and inversely proportional to the square of their distance apart."

This law in giving the principle of force gives also that of the movement produced by the force. It can be demonstrated by mechanics that Kepler's laws can be rigorously deduced from the law of gravitation.

We now know another fundamental law, the existence and the value of the pressure of radiation. It is by radiation, of which luminous radiation is the most obvious kind, that we are aware of the existence of the distant worlds with which infinite space is strewn. Apart from the luminous radiations perceived by the retina of the eye, there are other kinds which that organ is incapable of distinguishing. If a ray of sunlight be passed through a prism of quartz, and if the polychromatic image that is thus observed, and which is called a spectrum, be photographed it is found that the photographic image is prolonged some way beyond the extreme violet perceptible to the eye. There are thus ultra-violet rays of which our senses cannot inform us, but which the photographic plate registers. A very sensitive thermometer, placed in the region which precedes the red rays, discloses there infra-red rays imperceptible to the sight.

These radiations, to which must be added electric radiations and other forms that will probably be

discovered in the future, are the means whereby the forces of the universe are transmitted. The great physicist Maxwell first discovered, in 1873, that radiation exerts a veritable pressure, the power of which is measured by the quantity of energy contained in a unit volume of the medium transmitting it. Maxwell feared that the smallness of this pressure might render its measure impossible, but to the Russian physicist Labedeff is due the credit of achieving this difficult measurement. If we imagine a black body placed against the Sun's surface, the radiation emitted by this surface exercises a pressure of 2.75 milligrammes [.042 gr.] per square centimetre [.155 sq. in.] on the body. The illustrious Swedish physicist Arrhenius, to whom science owes a new outlook upon the formation of worlds, has been able to demonstrate mathematically that for a very small sphere, which is not transparent and of which the diameter is somewhat less than a micron, that is to say is less than a thousandth of a millimetre [.00003937 in.], situated in the neighbourhood of the Sun, the repulsive force resulting from the pressure of radiation would be greater than the attraction of the Sun's mass, and so the small body would be driven far away into space. If the diameter of the small sphere be supposed to

be less, assuming its density to remain equal to 1, the repulsive force would be increased, but such increase could not continue indefinitely, for, if the particle were much smaller than a wave-length of the light acting upon it, diffraction phenomena would be produced which would completely alter the nature of the light action. For particles having a diameter of .00015 millimetre, the repulsive force is ten times greater than the attractive one due to gravity.

The self-luminous bodies, the Sun and stars, thus have the power of driving away into space those very small particles of matter of low density, and these particles constitute the cosmic dust that permeates interstellar space. Particles similarly repulsed constitute the tails of comets, which are always directed away from the Sun, as if under the action of wind from the latter body. In all probability, the Solar Corona itself is composed of such minute fragments of matter. The dust particles that are thus repelled and flung into space by the stars are negatively electrified, the star remaining positively charged. Such of those emanating from the Sun, which reach the Earth, produce by their negative charges important electric effects, as we shall see later on.

In addition to the suns which shine in the

FIG. 1.—Great Nebula in Orion.

FIG. 2.—Spiral Nebula in the Constellation of Canes Venatici.

FIG. 3.—Planetary Nebula in Lyra.

heavens and which are bodies radiating heat, there are cold bodies in interstellar space whose useful purpose seems to be to arrest and absorb the heat energy radiated by the suns. If these did not exist, the infinity of stars scattered throughout space would give to the sky the aspect of a fiery vault, an incandescent dome, and their aggregate radiation would annihilate all manifestation of life at the surface of the habitable globes. These cold bodies are the nebulæ[1], they exist everywhere scattered through space. [However, where the stars are most numerous, in the Milky Way, the visible nebulæ are very scarce, and conversely the nebulæ abound where the stars are fewest.—*Ed.*] They can be seen in the clear dark sky as milky patches of light,[2] some without definite form or contour (Fig. 1), others with a roughly circular shape in which can almost always be traced a tendency to form a more or less sharply materialised spiral. [This form, in fact, predominates to a great degree.—*Ed.*] In some further cases the contour is still more definite. These

[1] While scientists are almost unanimous in agreeing that some light- and heat-absorbing medium does exist, it is not as generally accepted that nebulæ exist in sufficient numbers to be this medium.—*Ed.*

[2] Very few are visible without optical aid, only two in the northern sky.—*Trans.*

are the "planetary" nebulæ[1] which consist of a central nucleus surrounded symmetrically by an "atmosphere of light." Spectrum analysis enables us to study the composition of the nebulæ; their spectra are composed of bright lines similar to those which are obtained in our laboratories from incandescent gases. [This refers only to the so-called *green* nebulæ. The predominating type, the spiral nebulæ, known spectroscopically as white nebulæ, present spectra radically different.—*Ed.*] The characteristic rays given by hydrogen and by helium, a gaseous element originally discovered in the Sun and recently [1895. —*Ed.*] extracted from terrestrial sources, can be recognised, also rays from an unknown substance, not yet found in the Earth, to which the name nebulium has been assigned. Helium is formed by the molecular disintegration of the radioactive substances which exist in the solid crusts of the planets; possibly all the constituents of these, that is, all forms of matter, are radioactive. Both hydrogen and helium diffuse into space, where their thinly scattered molecules constitute the rarefied nebulous medium which only requires the coming of a nucleus for condensation to commence

[1] So named by Sir William Herschel because of their appearance, which is that of an ill-defined and hazy disk.—*Ed.*

there. Helium and hydrogen, therefore, might appear to be the ultimate products of the disintegration of matter.[1]

Whatever degree of precision the outlines of the spiral nebulæ show, streams of matter appear to diverge from a central point and to become more or less blended as they spread out, thus indicating a general movement of rotation of the matter composing the nebula. [The rotation of a spiral nebula was proved, in the spring of 1914, by spectrum photographs made at the Lowell Observatory. —*Ed.*] But one of the chief features of these objects is the existence in them of nuclei, more brilliant than the remaining part, apparently centres of condensation, around which the nebulous matter accumulates as it becomes more dense, thus giving birth to stars. The great spiral nebula in Canes Venatici is a remarkable example, in which there is also a second nucleus apart from the principal one (Fig. 2).

How do these condensation centres arise? Three explanations have been advanced. First, the contraction due to cooling through many ages suffices to increase the density at the centre, in consequence of which the velocity of rotation, and,

[1] Recent investigations have seemed to show the possibility of the transformation of hydrogen into helium.—*Trans.*

therefore, also the resulting centrifugal force, is augmented, thus causing the detachment of annular masses from the further parts of the nebula. This is what scientists, following Laplace, thought at the beginning of the nineteenth century. [It is now known, however, that nebulæ cannot be at a high temperature.—*Ed.*] Secondly, there is the explanation of modern astrophysicists, following Arrhenius, viz.: that, in the course of those innumerable centuries which are only an instant in the eternal history of worlds, "dead suns" enter the nebula and serve as nuclei for condensation. Thirdly, bodies, such as the Earth is now and as the Sun will be in the future, superficially cooled, but nevertheless containing in their heated internal masses a tremendous reserve of energy, have given birth, by collision with each other and the consequent partial volatilisation due to the heat disengaged by the shock, to a nebula for which the remaining portions of the original bodies serve as a nucleus, thus giving rise to a new star and so exemplifying the resurrection of a world. [The collision, or even very close approach, of two large absolutely *cold* bodies would produce practically the same result.—*Ed.*]

Whatever the original cause, the fact is almost certainly established that stars, that is to say,

suns, are produced from nebulæ by condensation of the matter forming these. When a fragment of cosmic dust penetrates into the midst of the nebulæ, it *falls* towards the centre of gravity of the whole, and the more the condensation progresses the greater the rise of temperature. The imperishable fame of Laplace lies in his having been the first to indicate the way in which our Solar System was derived from its original nebula.

Nebulæ, in their early stages, are composed of gases in a state of extreme rarefaction, of which the contents of a Crookes tube give us some idea. They retain what reaches them of the cosmic dust thrust outwards from the suns by the pressure of radiation. The nebulæ at first have the properties of gaseous masses in adiabatic equilibrium; that is to say, when they receive heat from neighbouring suns their temperature does not rise, but falls. Thus, according to Arrhenius, they have a negative specific heat. Since the cosmic dust is electrified a charge accumulates in the outer layers of the rarefied gaseous mass. It should be noticed that the temperature of a nebula must be very low, on account of its rarefaction, which implies an absence of internal movements and therefore of molecular collisions giving rise to heat. In all probability, the temperature of such a nebula is

about 50° C. [90° F.] above the absolute zero of the physicists, which zero has been definitely established by Amagat to be 273°C. [491.4°F.] below the temperature of melting ice, this latter being the zero of our thermometer [centigrade] for practical purposes. It is this recognition of the low initial temperature of the nebula which constitutes one of the most essential modifications that modern science has made in Laplace's theory of the evolution of the Solar System. He assumed that the nebula was originally at a high temperature.

Now, in spite of the low temperature we have been led to attribute to it, the nebulous mass emits light, and so is visible to us by reason of the luminosity with which its constituent materials shine. It seems remarkable how this state of incandescence can be maintained in these circumstances. It is due to the fact that, in proportion as the accumulating, electrified dust particles add an increasing quantity of electricity to the periphery of the nebula, the strain increases little by little, and ends by becoming sufficient for a discharge, analogous to that which takes place in a Crookes tube. This illuminates the entire mass, thus rendering it visible against the dark background of the sky. It should, therefore, be

noticed that we cannot see any such nebula in which the electric stress is not yet great enough to have produced discharge luminosity in the gaseous masses which compose its outer layers, so that the number of known nebulæ must be vastly, perhaps almost infinitely, increased if this number is to represent all that actually exist. In all cases, the production of luminosity is the first stage in the life of a nebula, hitherto, figuratively speaking, inert.

The second stage is the formation of a nucleus. Possibly a cooled body like the Moon or Earth comes in the course of ages and penetrates into the nebula, or denser masses of particles agglomerated together as meteorites similarly enter. Or perhaps the moving gaseous molecules collect in one part from some cause. Condensation at once begins around these intruded masses, as they may be called, which are therefore the means of starting the condensation process. This process sets heat free, and the nucleus, which grows continuously, gradually becomes incandescent, after having captured the greater part of the rarefied matter which constituted the original nebula. The system has now reached the stellar phase. As the condensation continues, the pressure at the centre increases and soon becomes very large.

The original hydrogen and helium, the residue of the disintegration of the matter of other stars, now become the origins of, or points of departure for, the integration of the matter of a new star.

It may also happen, as has been said above, that two dead suns clash together in the course of their journeyings through space, at some time or other. If they are constituted similarly to the Earth, their frail envelopes would be broken by the force of the shock and, independently of the enormous amount of heat disengaged by the impact, the fiery material set free by the rupture of the containing crust would rush out into space, being, for the most part, volatilised owing to the sudden decrease of pressure.[1] Two jets of spiral form would be produced, the whole rotating by reason of the obliquity of the impact of the two bodies. A new nebula may thus be created out of two dead suns. At its centre would be a new sun, or perhaps two or even more suns. This is an explanation of the appearance of those novæ or new stars which so strongly arouse the interest of astronomers. In all observed cases a spiral nebula has come into being with one or several incandescent

[1] The heat generated by the impact and the tidal strain in each body would be of far greater effect than the release of the heat existing in the inner parts of the two bodies; these in fact might be cold to the centre and yet be disrupted and volatilised.—*Ed.*

nuclei. Minor centres of condensation, arising perhaps from masses thrown out during the original collision, are found in the spirals. These secondary suns originate immediately after the primary one, drawing to them a part of the encompassing cosmic material; they gravitate around the central and more important sun, and so a planetary system is given birth.

The planets, at the commencement of their history, are formed of practically the same elements as the central nucleus. Carried round by the initial movement of rotation, they all generally revolve the same way, except in the cases where a strange body previously rotating in a contrary way may have penetrated into the exterior limits of the nebula, and so come into the field of attraction exercised by the new sun, the satellites of this body retaining their primitive rotatory sense on account of its mass. This is perhaps what occurred with regard to the outermost planets of our Solar System, Uranus and Neptune.[1] It is not necessary to assume that adventitious bodies entered the nebula to provide planets for the primitive central body. Laplace held that the centrifugal

[1] Other interesting and very plausible theories are propounded for the explanation of the rotations of Uranus, Neptune, and their satellites.—*Ed.*

force would suffice to detach successive equatorial rings from the mass of the principal nucleus, the speed of rotation of which increases in proportion as it contracts by cooling; that each of these rings afterwards would become a planet by the process of agglomeration of its material at one point; and that, in its turn, the planet might produce one or more satellites by an exactly similar method. [That the planets and their satellites could have been, and probably were, all built from the parent body or bodies and their particles and gases is accepted by the scientist of to-day. The equatorial ring theory of Laplace, is, however, no longer credited.—*Ed.*]

We have now, therefore, attained to the conception of a nebula having a principal centre of condensation, that is to say having a central sun and also secondary centres, whether formed by the intrusion of adventitious bodies or arising from the condensations and agglomerations of matter detached from the principal mass first, possibly by the initial catastrophe or later by the agency of centrifugal force. The subsidiary centres begin to gravitate around the chief one, describing elliptical orbits, the form of which was defined by Kepler, who also first stated the laws of the planetary movements. The secondary nuclei

begin to rotate on their axes in consequence of the initial movement of rotation of the primitive nebula. We shall here only consider one of these bodies, the Earth.

From the time when it was separated from the central nebulous mass, the Earth's individuality commenced, but it had not yet become what may be called the terrestrial globe. Before doing so, it had to cool and consequently to contract. It can be shown by mechanics that the velocity of rotation increased as the diameter diminished. Centrifugal force caused a mass of matter to be detached from the Earth's equator, the Earth having been previously flattened to the shape of an orange by the same agency, [and later, just before the mass broke loose, drawn out into a somewhat pear-shaped form.—*Ed.*] This detached body took the normal spheroidal form round a nucleus, the small mass of which permitted a more rapid cooling. Thus, the Moon was formed and has subsequently continued its revolution about the Earth.

The temperature of the detached Earth fell much more quickly than that of the central Sun, which, on account of its enormous mass, 325,000 times that of the Earth, cooled with extreme slowness, just as of two pieces of iron heated red hot

in the same fire the greater remains warm a much longer time than the smaller. The mass constituting the Earth, therefore, passed gradually from the gaseous to the liquid state, and then to a viscous condition. Its rotation, which implied a concomitant centrifugal force, then caused the equator to bulge out and, also, the polar regions to become flattened. [It was succeeding this that the Moon was cast off.—*Ed.*] In proportion to the extent of the cooling, some of the gaseous elements which constituted its atmosphere, dissociated and kept from combination by the high initial temperature, were enabled to condense, as, for example, metals that were originally vaporised, and others to combine together when they arrived at a sufficiently low temperature. As the cooling steadily proceeded during this time, the globe came to solidify at its exterior surface, and therefore to be covered with a crust which, although very thin at first, gradually thickened until it served to maintain a kind of equilibrium between the escaping internal heat, which it transmitted badly, on account of its feeble conductivity, and the external heat received from the central Sun.

Thus, we have a globe, flattened at the poles and protruding at the equator, covered by a solid crust, and of which the chief part consists of in-

candescent material at a highly elevated temperature. The crust is encompassed by an atmosphere in which were originally present the vapours of all substances volatile at the temperature of solidification of the materials which constituted the solid crust. The Earth has come into being.

## CHAPTER II

### THE AGE OF THE EARTH

WE have now to consider the first stage of the existence of the Earth, the origin of which was characterised by the formation of a superficial crust, the first rudimentary state of that solid ground on which we actually live.

This crust or shell, due to the cooling of the exterior layers of the heated and rotating spheroid, had the effect of preventing the rapid cooling of the fused layers beneath, which thus retained their high temperature. Immediately beneath the solid stratum were liquid and gaseous masses in motion, while near the Earth's centre the fused matter, liquid or even gaseous, subjected to the enormous pressure of several millions of atmospheres by reason of the weight of the exterior layers, probably existed in a condition practically equivalent to the solid state, compressed as it was beyond any pressure realisable in our laboratories. The heated nucleus would contain all the chemical

elements, since it came from a portion detached from the solar matter, and since the spectroscope proves the existence of all these elements in the Sun. But there would certainly be an excess of iron, for, in the first place, spectrum analysis of the light of the stars teaches us that iron predominates in them from the first phase of their evolution. Secondly, the actual general magnetic state of the Earth at the present time indicates, by its effect on a magnetised needle, the presence of magnetic materials in considerable quantity at the centre of the globe. Furthermore, these materials are found in the lava which flows at intervals from volcanic craters over the surface of the Earth.

De Launay has shown that it is possible, by means of geological considerations, to assign the order of superposition of the most widely occurring chemical elements, at the time when the Earth had ceased to be entirely fluid. The elements may in this way be classified into seven groups, the first of which is represented by hydrogen, and the last of which contains the heavy precious metals. The atomic weights would increase with the depth and therefore the elements would be found in the crust at distances from the centre in inverse proportion to the atomic weights. The

atoms, freed from chemical affinity at the high temperature in question, individually obeyed, in the fluid rotating sphere, only the laws of gravitation and centrifugal force.

Above the crust thus formed exists an atmosphere which is, at first, at the temperature of solidification of the rock. The latter was, therefore, formed by the solidification of the most refractory, that is to say the least volatile, elements. The first minerals appearing at the surface would be combinations of silica with alumina, also lime, magnesia, and a little iron and soda.

The terrestrial crust, which was at first very thin, played an important rôle; it separated the interior incandescent nucleus from the layer of gases and vapours which surrounded the Earth. This gaseous envelope or atmosphere, the remaining constituents of which envelop our globe at the present time, originally contained a considerable proportion of carbon dioxide gas, which was emitted continuously by the turbulent fluid interior matter. It contained also light gases, notably hydrogen which was present in very large quantity; spectrum analysis demonstrates its existence in the atmospheres of the distant planets, such as Uranus and Neptune, which are in the process of evolution. The atmosphere also contained hydro-

carbons and considerable quantities of oxygen and nitrogen.

When the solid terrestrial crust was definitely formed, it was at a very high temperature, namely that of its solidification. It could not, therefore, retain light gases such as hydrogen and helium, which were dissipated into the solar nebula, and thence passed out into intersidereal space where they constituted rudimentary nebulæ. These gases now exist, in the lower regions of our atmosphere, only in very minute traces; at a height of 100 kilometres [62.5 miles] from the ground the little atmosphere which remains is probably composed approximately of 99½% of hydrogen and ½% of helium.

Thus, when the crust was completely formed, there remained as atmospheric constituents a great quantity of nitrogen and also a large proportion of carbon dioxide and water vapour, for almost all the oxygen was in combination with hydrogen, forming water, which the high temperature prevented from condensing to liquid form. Water cannot exist in the liquid state above the temperature of 360° C. [680° F.], which is called its critical temperature.

As the temperature of the atmosphere gradually fell, the most volatile metals remaining in the

form of vapour, such as potassium and sodium, were the first to condense. Then, as the cooling continued, elements which the high temperature had prevented from combining were now able to do so, and thus chlorides, bromides, iodides, etc., were produced. When the temperature had decreased to below the critical one of 360° C. [680° F.], the water vapour began to be precipitated in the liquid state. The original pressure of the atmosphere must have been very considerable, since it contained in the gaseous condition the whole of the water actually existing on the earth at the present time. Now, if the oceans were distributed uniformly over the Earth's surface, they would form a layer of water of more than 3000 metres [1.9 miles] in depth, exercising a pressure of 300 times that of our present atmosphere; and this water as vapour would have exerted an equal pressure in the early atmosphere.

During this period, the solid, but still thin, crust was continually kept in a state of agitation by the bubbling up of the internal mass, the upper layers of which, liquid or gaseous, came into contact with and pressed against its inner surface. Under these repeated attacks, the crust gave way in places, and became pierced with craters, fissures, and crevices which allowed the upward pressing

fused matter to escape. At the lower temperature of the surface, this matter solidified, thus giving rise to the formation which geologists call Archæan, through which jets of the interior magma burst forth, producing the eruptive rocks on solidification. This, however, is not all. On account of the continuous cooling, due to the thinness of the primitive crust, the latter, not being completely sustained by the interior contracting mass, sank in certain parts when the internal pressure raised up other parts. The outer surface of the solid part of the globe, that is the surface of the lithosphere, would therefore not be uniform; it became wrinkled and indented, presenting protuberances and hollows.

When the atmosphere cooled to the critical temperature of 360° C. [680° F.], and the water vapour consequently began to condense to the liquid state, the latter fell as scalding rain on to the solid surface. This water condensed on the higher portions of the surface and flowed down the declivities, dissolving a greater or less proportion of all the substances distributed over the surface of the terrestrial globe. Thus, the streaming of the water commenced on an extensive scale. The water accumulated in the cavities, the folds, and the hollows of the solidified crust, in accordance

with the laws of gravity. In this way the oceans first came into being, and it is probable that, as they resulted from the accumulation of water which was originally hot, and which had bathed the entire surface of the Earth, they would have dissolved in the process everything that could be taken into solution and that, therefore, they would contain, at any rate in traces, all the elements which were to be found in the enveloping crust of the Earth.

We shall now examine the form taken by this shell, the lithosphere, the hollows of which received the waters of the primitive seas, and whose higher emerging portions constituted the original continents.

If the superficial crust had continued to envelop a nucleus which sustained it at every point, that is to say with which it was in perfect contact, this solid stratum would have simply taken the form of the fluid nucleus, slightly flattened on account of the centrifugal force due to the Earth's rotation. The crust would thus have the geometrical form of an ellipsoid of revolution. But its support was imperfect, on account of the slow contraction of the central mass due to cooling, and, therefore, as has been said above, it became folded and wrinkled and covered with inequalities, hollows

in some parts, protuberances in others. These suffered frequent changes in the early periods, but such changes became rarer and less widespread as, in the course of time, the Earth evolved towards its actual present condition.

Were these foldings produced quite by chance as might be supposed from a superficial examination? We know that chance does not exist and that what we so designate is only the resultant of a number of forces or conditions of which we are more or less ignorant. Everything in that wonderful machine, the Universe, is regulated by inflexible laws. The foldings of the terrestrial crust were not produced erratically; their formation was in accordance with the law of tetrahedral symmetry. At the time of its origin the crust took a certain form which it would tend to preserve unchanged. In order that it should change as little as possible, when the interior volume came to diminish in consequence of the contraction of the nuclear mass, the crust should have a regular figure corresponding to the minimum content for the given surface. Geometry teaches us that the tetrahedron, a regular solid figure with four triangular faces, a pyramid with a triangular base, satisfies this condition. Many causes would operate against the crust taking this form in its

entirety, but it would at any rate indicate by the direction of its folds a *tendency* to take the tetrahedral shape. This tendency would manifest itself in the diametrical opposition of the continents, since these represent the emergent apices of the tetrahedron, and a similar opposition in the case of the oceans which correspond to the plane faces of the pyramid. These faces are necessarily below the surface of the seas which thus make up the flattened spheroidal form imposed on the Earth by the combined action of the laws of gravity and centrifugal force. (Fig. 4.) Thus from the simple fact of the contraction of the internal mass we are able to form some idea of how the fundamental division of the surface into land and water came about, a division which remained for a long time one of the mysteries of geographical science.

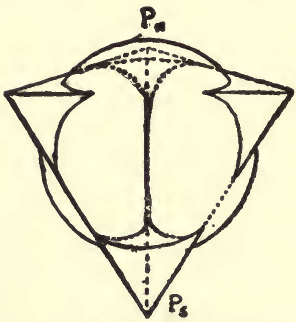


FIG. 4.—The Terrestrial "Tetrahedron."

There is another point to be noted about this tendency to take the tetrahedral form. The edges, or *arêtes*, of the tetrahedron have also an essential significance; they indicate the general

orientation of the emergent land which runs roughly north and south. We will return at a fitting time to this important subject from the point of view of the figure of the Earth.

We are, henceforth, able to distinguish two very distinct things: first, the lithosphere which is formed by the solid shell of the globe, a shell originally spheroidal and later deformed by the foldings and furrows of its surface brought about by the tetrahedral laws, at any rate as regards the essential features; and, second, the hydrosphere, formed by the water surface, the fluidity of which causes it to be governed by the laws of gravity and of rotation, and which maintains, save for slight local perturbations in the immediate neighbourhood of the continental masses, the flattened ellipsoidal figure which is a necessary result of the laws of mechanics.

We shall have to return in fuller detail to the tetrahedral theory in the course of this work; we shall find its application to the theory of seismic phenomena, those eruptions, which are due to the impulse of the heated internal mass and which constantly agitate and dislocate the crust of the earth.

The condensation of the atmospheric water vapour, which began at a high temperature, sub-

sequently continued and its extent increased as the cooling went on. The temperature fell little by little and when it reached the neighbourhood of 55° C. [131° F.], the conditions required for life were realised. Given a living germ, it could grow, reproduce itself, and evolve, that is to say, organised beings could prosper. Furthermore, since the cooling was not rapid, a state of equilibrium was established between the total heat received from the Sun and from the heated interior of the Earth on the one hand and the loss by radiation on the other hand, in such a way that the conditions of temperature favourable to the existence of living beings were brought about in due course. The torrents of water which streamed over the continents carried the debris washed therefrom into the sea and deposited it at the bottom of the oceanic hollows. Thus the process of sedimentation commenced; the primitive rocks were all of igneous origin, but now other kinds began to be formed by the superposition of successive deposits on these original rocks.

Hence was instituted the history of the early ages of the Earth, its geological history, which is that of the time prior to the appearance of man on the globe.

At the period of which we are speaking, the

crust was a rigid shell having a composition analogous to that of granite, and the oceans existed, but frequent changes occurred in the configuration of the continents and seas in consequence of the convulsions of the still weak crust, under the influence of the outward thrust of the interior mass. The primitive atmosphere was rich in water vapour and carbon dioxide and did not yet contain all the oxygen necessary to maintain life, a part of which still remained combined with carbon. Thick clouds floated in it on account of the superabundance of uncondensed water vapour.

The large proportion of carbon dioxide in the atmosphere at this period gave to the latter a remarkable property which the actual atmosphere at the present time does not possess to anything like the same extent. It played the part of a protective screen, keeping in the heat and consequently lessening the rate of the Earth's cooling. Carbon dioxide now constitutes scarcely $\frac{1}{3000}$ part of the air, but calculations based on experimental evidence have led Arrhenius to the conclusion that if this small quantity of gas were absent the temperature of the Earth's surface would fall 21° C. [37.8° F.]. This would further lead to the condensation of a large part of the

aqueous vapour still present. As this also acts as a retaining screen in the same way as the carbon dioxide does, it will be seen that the disappearance of this gas would bring disaster upon the Earth, from the point of view of temperature.

Conversely, it will be readily understood how in the early ages of the Earth's history the protecting mantle, formed by an atmosphere considerably richer in carbon dioxide and water vapour than our present one, enabled the soil to maintain the high temperature that caused the extraordinary development of vegetation characterising that period.

or till Devonian.

From the epoch of the solidification of the crust up to the present time, the history of the Earth is called Geology. It is outside the scope of the present work to trace it in all its details. M. de Launay has given an authoritative exposition of it in his masterly work *The History of the Earth.* We will confine ourselves here to an outline of the chief facts.

That part of the original solid crust which was covered by the oceans due to the condensation of the atmospheric water vapour, oceans that were destitute of beaches, constituted the foundation upon which all the later solid formations came to be built up. The first disturbances of the primi-

tive crust, the first foldings that it experienced, produced high lands and depressions, thus fixing the original distribution of the continents and seas. The Archæan rocks, that are invariably met with when the soil is penetrated deeply enough to get below all the superincumbent strata, are the oldest known rocks. During the period of formation of the Archæan rocks eruptions from the central mass into crevices of the thin crust were frequent and the Plutonic rocks were produced by the solidification of the interior material thus pushed up. In fact by the study of the Earth's crust we find only the granitic or Plutonic rocks underlying the crystalline or Archæan rocks.

The great thickness of the Archæan formation, which in certain regions is 10,000 metres [6⅓ miles] or even more, indicates the enormous duration of this first period of the Earth's history.

The rocks formed were still at a high temperature and the primitive atmospheric condensation brought down scalding liquids, so that the conditions at this time were not suited to animal or vegetable life. It is, therefore, not remarkable that we find no trace of any living thing in these first strata. Possibly elementary life made its appearance at the end of this period, but any such creatures being destitute of hard or bony struc-

tures left no trace of their existence on rocks so hard and at the same time so convulsed as those which form the Archæan strata.

In proportion as the atmospheric temperature and therefore that of the first oceans fell and reached the neighbourhood of 60° C. [140° F.], the terrestrial conditions began to be such as would admit the possibility of life. But how did life make its first appearance in the world? Perhaps wandering cells driven from another world by the pressure of radiation reached the Earth and lived and evolved thereon, having resisted the influence of cold during their long journey through space, the possibility of which resistance has been demonstrated by work in the laboratory at Leyden. Arrhenius is of opinion that they must also have escaped from the destructive action of the ultra-violet rays. Or perhaps life originated on our globe in some other unknown way. The problem is one which is at present unsolved and will doubtless remain so for a long time. What is certain is that the Primary Era, characterised by the appearance of life, vestiges of which remain to us as animal and vegetable fossils in the strata of this period, began after the stage represented by the Archæan rocks. The strata corresponding to this era are classified

by geologists into Silurian, Devonian, Carboniferous, and Permian.

As previously explained, the atmosphere, rich in carbon dioxide and water vapour, formed around the earth a protective screen preventing rapid cooling and maintaining an extremely high temperature at the surface of the ground. Consequently vegetable life all through the Primary Era, but particularly in the Carboniferous period, flourished with an extraordinary fertility. The remains which are found in coal-beds show that vegetable species, which are to-day merely small plants, were then veritable trees, forming great forests. There were at first only cryptogams and later also gymnosperms. With regard to animals it can be affirmed that life commenced in the seas. The first beings were invertebrates; it is only at the end of the Primary Era that the first fishes, having vertebrate bony systems, are found. There were neither birds nor mammals. It is however remarkable that the first animals whose remains can be found, the trilobites, show an organisation sufficiently high to indicate that they were products of an already advanced evolution. It is a far cry from elementary cells to trilobites.

The great activity of the primary vegetation

has had a decisive influence on the history of the globe. The absorption of carbon dioxide by the abundant vegetation restored free oxygen to the terrestrial atmosphere and produced little by little the quantity actually present. Furthermore, the minerals first formed, combinations of silica with lime, alumina, magnesia, iron, and soda, had gradually been attacked by the carbon dioxide of the primitive atmosphere, largely by the agency of water which contained the gas in solution on account of its prevalence in the air. Lime, magnesia, soda, and iron were thus converted into soluble carbonates and accordingly carried down to the seas by the water-streams and accumulated there. The first living beings assimilated these substances, as their remains, deposited in sedimentary layers, testify. In fact the formation of sedimentary limestone and dolomite required 34,000 times more carbon dioxide than is actually present in the air. Thus large quantities of this gas must have been removed from the atmosphere in addition to what was decomposed by vegetable life.

It can legitimately be stated that almost the whole of the actual free oxygen of the air is due to the vegetation, especially that of the Primary Era.

An era of calm and stability then succeeded. This is called the Secondary Era and geologists sub-

divide it into the Triassic, Jurassic, and Cretaceous periods. It commenced as the atmosphere, by the gradual diminution of carbon dioxide and the increase of oxygen, became more and more suitable to the development and evolution of living creatures. Other characteristics were the gradual decrease of temperature, which was still high, and the greater stability of the Earth's crust, strengthened and thickened by successive solidifications.

The fossil remains of life which are met with in these strata, which are always superimposed on Archæan or Primary formations, clearly differentiate this era from the preceding one. As regards the vegetation, the prevalence of cryptogams ceased in the Secondary Era while gymnosperms were everywhere predominant. The first living beings whose traces have been found, the trilobites of the Primary Era, had completely disappeared. In their stead were belemnites, the forerunners of our present cuttlefish, and ammonites which were cephalopods with spiral shells; these were characteristic of the era. In the seas, crinoids, sponges, and corals were abundant and foraminifera and radiolaria developed. Their hard parts accumulated in thick layers and by this sedimentation process covered the bottoms of the seas of that period. Thus the work of the ocean began,

a work which still continues without cessation in our present seas; geology is mainly the oceanography of the past, and the study of oceanography forecasts the geology of the future.

But the characteristic feature of the Secondary fauna was the evolution of vertebrate animals; the armoured fish of the Primary period had disappeared, having little by little given place to fish with well-ossified vertebræ. In particular, gigantic reptiles came into being, the colossal size of whose skeletons fills us with astonishment. The ichthyosaurus, the plesiosaurus, and the mosasaurus were the monsters that peopled the seas, while the continents were inhabited by immense creatures, dinosaurs, some of which attained a length of twenty-five metres [82 ft.] and a considerable height.[1] When one sees, in the palæontological galleries of museums, the skeletons of iguanodon, brontosaurus, stegosaurus, and diplodocus, one cannot help being struck by the manifestation of strength that these gigantic animals represent. When standing erect, some of them would have overtopped the roof of an ordinary five-storey house. Finally, the first birds made their appearance in Secondary times, and when the gigantic

[1] Quite recently, remains of a huge creature about double this length have been found.—*Trans.*

cold-blooded animals, which have just been mentioned, were predominant, in consequence of their size and strength, much smaller animals, the first warm-blooded mammals, had their origin. The geography of these times was characterised by two continents in the northern hemisphere separated by an ocean in the midst of which was emergent land corresponding to the actual situation of northern Europe. In the southern hemisphere a vast continent stretched over the position of South America and Africa; the South Atlantic Ocean did not exist and land marked the future place of Australia. Volcanic eruptions were less frequent, the Secondary Era being, as above remarked, a period of relative tranquillity.

This state of calm came however to an end and gave place to violent convulsions; the volcanoes manifested great activity, increasing to a state of paroxysm, and at the same time arose the great mountain chains which are actually present on the globe. During this time animal life was gradually perfecting its forms and was producing creatures more and more resembling present ones; and mammals, some of which attained gigantic dimensions, were masters of the land surfaces. As examples, we have the palæotherium, the hipparion, the colossal dinotherium, the mastodon (the first

elephant), the hippopotamus, the rhinoceros, the great deer, ruminant and carnivorous animals. This formed the Tertiary Era, subdivided by geologists into the Eocene, Oligocene, Miocene, and Pliocene periods. Palms abounded at first, but towards the end of the era trees appeared which resembled those of our present forests, while tropical flowers narrowed their habitat to the neighbourhood of the equator.

The emergent lands approached more and more to the present continental contours. The great tertiary chains of the alpine type which now surround the Mediterranean basin arose as a result of mountain-forming movements of great intensity. After the retreat of the sea which invaded certain parts of France, the shocks recurred and volcanic eruptions became formidable; the Central Plateau became covered with craters which emitted the lavas now visible in Auvergne, and the actual features of the land surface gradually became established.

During this time, the atmosphere continued to lose carbon dioxide and water vapour, and the cooling of the Earth by radiation became greater, so that the temperature fell little by little, still remaining, however, higher than the mean temperatures now observed in the same regions. The

nature of the remains of vegetation shows that the mean temperature of France was more than 25° C. [77° F.], that is to say the climate of that country was similar to that which characterises the equatorial regions at the present time. It was only at the end of the Tertiary Era that the temperature was lowered and glaciers appeared on the highest mountains and commenced their extension towards the lower regions. When this occurred, the fauna and flora of the warm climate gradually receded towards the tropics, abandoning the northern lands where the initial climatic conditions of the Tertiary Era had allowed them to flourish, but whose more rigorous later climate was too cold.

The Earth slowly attained its present aspect. The vegetation had developed into the forms with which we are now familiar; the animals had evolved and had reached a kind of perfection. The environment was thus ready for the existence and development of the creature which came to dominate nature, that is to say Man, and the Quaternary Era began.

The Quaternary strata have a very different character from the preceding ones; exterior agencies predominated in forming them. They cover all the others and are themselves covered only

by the soil-cap. They are alluvial deposits, the consequence of enormous precipitations of rain, due to the condensation of water vapour on a large scale, following the great lowering of temperature caused by the almost complete absorption of carbon dioxide. These abundant precipitations, which probably constitute the origin of the story of the Deluge which exists among all peoples, led to great rivers. Snowfalls, prevented from melting by the fall of temperature, caused an enormous extension of the glaciers, which at that time covered the whole of Central Europe and all North America. The ground is covered with erratic blocks, indisputable evidence of the existence of glaciers in the first part of the Quaternary Era, to which geologists have given the name of Pleistocene epoch. This glaciation consequently led to the migrations of animals, because of the great climatic variations which resulted from it.

These rivers deposited the Quaternary strata, in which may be found precious stones, gold, and platinum. Above the Pleistocene deposits are the different recent strata composed of clay, fine sand, and silt which are utilised for cultivation.

At the end of the Quaternary Era, the volcanoes of Auvergne again became active, and distinct evidence of this relatively recent renewed activity

may be seen at the present time on the Puys chain. Later on, the glaciers retreated, and the present climatic conditions established themselves by degrees.

The great mammals, the mammoth, rhinoceros, cave bear, and great elk have since disappeared; so also has the megatherium of South America. Diminutive specimens of the wingless birds from which ostriches and cassowaries are derived still exist in New Zealand and are called kiwis, but they are rare.

It is, also, in this latter country that the least civilised natives are found, natives who approach the nearest to a purely natural condition and who are able to afford us some idea of primitive man.

Man made his appearance on the Earth in the Quaternary Era. His presence is proved by the remains of human bones, which have as yet only been found in Quaternary strata, never in any of the preceding formations, and also by the remains of objects unmistakably his handiwork. In the earliest stage, during the prehistoric period, are found only implements formed of hard stone; flints rudely hewn by chipping. This is known as the Palæolithic period, that of chipped stone, which gave place to that of polished stone, the Neolithic period. Subsequently to the latter,

metals began to be worked, first of all bronze, in the bronze age, and secondly iron, in the iron age.

The history of mankind commenced from this time.

Such are the stages passed through by the Earth in the course of its early years, during its infancy and youth, before arriving at the state of maturity to which it has now attained. One very important question suggests itself to the mind: How many years has that slow evolution taken? Or in other words, what actually is the age of the Earth? It is very difficult to give an answer, at any rate a precise one, but in default of an exact knowledge of the length of time the Earth has been in existence, we may get some idea of the magnitude of the period which has elapsed since the crust solidified and enclosed the heated nucleus, the result of its stellar origin.

This evaluation may be approached in different ways. We may for example ask ourselves what time must have elapsed in order for the oceans to have acquired their actual salinity, by the accumulation of material that the streams brought down in solution from the solid crust over which they flowed. Joly has attempted this estimation. He calculated how much salt the rivers annually carry to the ocean and by comparison of this

quantity with the amount that sea-water actually contains he arrived at the conclusion that at least a hundred million years must have been necessary for the present salinity to have been acquired in this way. It will not serve a useful purpose to describe how this estimation was attained. At the beginning of the aqueous condensation, the water flowed at a high temperature over the lands then formed and so it dissolved much more of saline substances than can the cold water of the rivers which at the present time flow into the sea. For this reason, however ingenious the above estimate may be, it furnishes us with very uncertain data as to the Earth's age.

The phenomenon of sedimentation enables us to arrive at a much more probable evaluation, which Sir Archibald Geikie has made. If the total thickness of the sedimentary deposits forming the stratification of our globe be estimated at about 30,000 metres [19 miles], and if it be assumed, as the work of geologists has shown that between three thousand and twenty thousand years are required for a layer one metre [39.37 in.] thick to be laid down, it follows that, in round numbers, the time necessary for the depositing of all the known strata is between a hundred and a thousand millions of years. This, moreover, takes no

account of Pre-Cambrian formations which have existed perhaps as long again.

The discovery of the phenomena of radioactivity made by the French physicist Henri Becquerel, and the important researches, which these discoveries have led to, have given modern geo-physicists another basis of estimation. It is known that the emanation of radioactive substances, such as radium, thorium, or even uranium, becomes transformed into helium. The English physicist Rutherford, to whom we owe the discovery of the emanation, has determined by experiment how much a given weight of uranium or thorium loses as helium in the course of a year. Also, Sir William Ramsay has studied the minerals from which uranium and thorium can be extracted and has determined the proportion of helium therein contained. From his results, Rutherford states that at least four hundred million years must have been required for these minerals to be formed in their present state. It will be seen that this result is in harmony with the result deduced from sedimentation, being at any rate of the same order of magnitude.

The phenomena of radioactivity which have also been brought into requisition to explain the constancy of the emission of heat from the Sun,

have enabled us, in recent years, to estimate the age of the Earth with more and more precision. English physicists, in particular, have done notable work in this direction. Starting from the quantity of helium contained in minerals the following duration periods have been assigned: three million years to the Greensand, six million to the basaltic rocks of Auvergne, fifty-four million to certain Norwegian rocks, two hundred and eighty-six million to some of the rocks of Ceylon, three hundred and twenty million to the blue earth of Kimberley, and six hundred million to the Archæan formation of Ontario. Thus figures similar to those of Joly, Geikie, and Rutherford are reached. A study of the Swedish rock-masses leads to still greater figures, the age indicated for them being a thousand or thirteen hundred million years. Some American formations give results of thirteen and fourteen hundred million, and, in conclusion, specimens of rock from the neighbourhood of Colombo in Ceylon have had assigned to them an age of more than sixteen hundred million years.

Thus, the maximum result of estimations based on the duration of sedimentation, viz., one thousand million years, is surpassed. We shall find that the figures in question are confirmed by quite different considerations, of an essentially geo-

graphical character. For geographers have also contributed knowledge of the Earth's age. They have studied the folds of which we have spoken previously and which constitute our mountain chains. These foldings were caused by the fact that, owing to the cooling and contraction of the nucleus on which it originally rested, the crust was no longer sustained from below and consequently contracted, becoming shrivelled as in the case of the skin of a fruit when it dries and becomes smaller. If the surface area of the mountain chains be measured in square kilometres, not in projection, as upon maps, but in reality on their sides, it is found that this total area is about one hundred and fiftieth of the entire surface of the globe. The corresponding decrease in the length of the Earth's radius can be deduced; it is a little less than $\frac{1}{100}$ part of its value, and this contraction would correspond to a lowering of temperature of more than 300° C. [572° F.]. To produce this fall nearly two thousand millions of years must have elapsed.

As a result of all that has been said, we may consider it probable that the actual age of the Earth lies between one thousand and two thousand million years. It is both interesting and very remarkable that estimations based on such

different methods give results that are sensibly concordant.

Finally, before concluding this account of the Earth's history, we have to ask ourselves whether the terrestrial crust on solidification was of a uniform thickness surrounding the fluid nucleus, or whether the foldings produced during the first movements of the shell had an influence on the thickness of the solid stratum.

Evidently the crust did not solidify as a whole at one time. It would pass through stages similar to those that can be observed in baths of molten metal. When solidification begins, solid crusts or scoriæ form in places and float on the surface of the rest of the liquid mass. Certain astronomers have put forward the rather daring theory that the spots on the Sun are simply the first scoriæ so formed, indicating the beginning of a partial solidification. On this theory, matter thrown to a distance by the solar eruptions consequently cools and falls back on to the liquid surface, on which it floats as icebergs float on water.

It is very probable that this occurred in the case of the Earth during the formation of its crust; solid pieces or plates, separate from each other and floating in the main fluid mass, were first formed. Lippmann has suggested the following

ingenious hypothesis. Since, as he says, the crust resembles a kind of irregular mosaic formed of floating fragments in juxtaposition to each

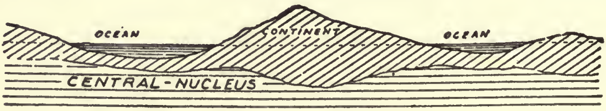



FIG. 5A.—Lippmann's Hypothesis on the Earth's Crust.

other, each portion must be sustained from below by a sufficient upward thrust exerted by the fluid mass in which it floats. If, therefore, a given piece carries a considerable mountain mass the weight of the load is much greater than in the case of a piece above which there is a sea, particularly as the density of the solid mass is so much higher. It, therefore, follows that the floating portion of greater weight sinks to a deeper level in the incandescent fluid than the other. It has a greater draught, to use a nautical expression (Fig. 5A), and consequently the crust should be thicker under the continents than under the oceans (Fig. 5B).

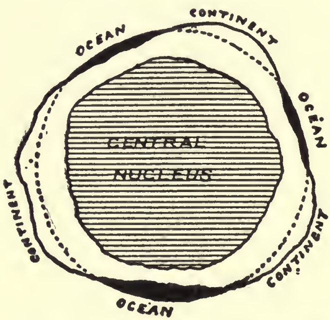



FIG. 5B.—Lippmann's Hypothesis.

We shall see later on how this hypothesis accords with recent determinations of the intensity of gravitation.

We have, if not a precise value, at any rate some idea of the order of magnitude of the age of the Earth. Geologists estimate the duration of the respective eras as follows: 75 per cent. for the Primary Era, 19 per cent. for the Secondary Era, and 6 per cent. for the Tertiary Era.

## CHAPTER III

### THE FORM, MAGNITUDE, AND MASS OF THE EARTH

WE have now reviewed the successive states through which the Earth has passed before reaching that with which we are familiar to-day. The periods with which we have dealt in the course of the preceding two chapters correspond to the birth, the infancy, the adolescence, and the youth of the Earth. To-day it is mature; let us see in what manner it "exists" and how it "lives."

We must first of all gain some idea of its external aspect, and we will commence by investigating its form and dimensions.

The proofs that the Earth is a spheroidal body, isolated in space, have been summarised in our earlier pages. It is possible to give a preliminary notion of its dimensions by remarking that a telescope, whose axis is truly horizontal, mounted on the summit of a mountain overlooking the sea, would not show the sea horizon. In order to have this horizon in view in the centre of the field of

the instrument, the latter must be rotated downwards through an angle which astronomers call the "angle of depression." If this angle be carefully measured, and if the height of the mountain be also known, we can deduce the Earth's radius by means of elementary geometry, on the assumption that it is a true sphere. As a first approximation, the result so obtained is 6,366,000 metres [4000 miles]. It is noteworthy that if this experiment be repeated in different parts of the Earth nearly the same result is always obtained. We may therefore assert that the Earth is sensibly spherical and that its radius is 6,366,000 metres, to a first approximation.

If we now make a more precise and accurate determination of the angle of depression by employing a more powerful telescope, capable of rotation about a more exactly divided circle, and if, further, we increase the magnitude of the angle to be measured by taking our station on a high mountain surrounded by sea, for example the summit of the Peak of Teneriffe, an unexpected result is obtained. Measured in the north direction the angle of depression is greater than when the instrument is pointing east or west. In the case of the Peak of Teneriffe, which rises for 3710 metres [12,000 ft.] above sea-level, the difference between the two

values so measured is twenty-eight seconds of arc. Hence it may be deduced that the Earth must have the form, not of a perfect sphere, but of an ellipsoid of revolution, flattened at the poles and bulging at the equator. The polar flattening may even be determined from this difference, and is found to be $\frac{1}{300}$ part of the equatorial radius. This flattening is a necessary consequence of the original formation of the Earth; while still fluid it rotated around the line joining the poles, and the centrifugal force resulting from the rotation produced the polar flattening and the equatorial bulge.

The above-mentioned method of measuring the dimensions of the Earth is subject to error, because of the deviation produced in luminous rays slightly inclined to the horizon by atmospheric refraction. It is, therefore, necessary to find a more accurate way of arriving at the required result. Nevertheless it gives us some knowledge of the general shape of our globe and furnishes us with sufficiently accurate data to form an idea of the order of its dimensions.

Maps of the Earth show that water, in the form of oceans and seas, covers nearly three-fourths of its surface. Oceanographers, from the time of Maury to that of the Prince of Monaco, have

explored the sea-depths by soundings, and the greatest depth reached is not quite 10,000 metres [6 miles]. On the other hand, the highest terrestrial mountain, Mt. Everest, does not reach a height of 9000 metres [5.6 miles]. The protuberances and the hollows are thus very small in comparison with the dimensions of the Earth, although they appear to us very considerable. The greatest heights and depths of the surface are only $\frac{1}{700}$ part of the radius, that is to say, scarcely $\frac{1}{1500}$ part of the diameter, of the Earth. If they are to be represented, exactly to scale, on a relief globe, we must take a globe one and a half metres [4 ft. 11 in.] in diameter. Even then Mt. Everest, with its 8800 metres [5.6 miles] on the one hand, and the great oceanic hollow in the Pacific, 9750 metres [6 miles] in depth, on the other hand, will be represented by a height and depression respectively of only about a millimetre [.039 in.].

The familiar comparison of the Earth's irregularities to the wrinkles on the skin of an orange errs, therefore, on the side of exaggeration of the former. The Earth's relief is very much less, relatively, than that of the orange.

There is a special science, Geodesy, the object of which is the exact measurement of the Earth

and the determination of its form. If the Earth be spherical, an arc of the meridian joining any two points upon its surface, separated by a fixed number of degrees of latitude, would have always the same length, whether near the pole or the equator. If, on the contrary, the Earth be ellipsoidal, an arc of the same number of degrees will be longer near the pole, where the surface is flattened and the radius of the curvature consequently greater, than near the equator where the radius of curvature is smaller.

The measurement of meridional arcs is of such extreme importance that the civilised peoples have combined together to form an International Geodetic Association, which meets every three years in a different capital, for the purpose of examining the results attained and settling the programme of new researches to be made, the new arcs to be measured. This association has also collected values of the intensity of gravitation which enable us, by the difference of the attraction exerted on a pendulum in making it oscillate more or less quickly, to determine the law by which attraction varies according to the distance from the centre of attraction. Hence we have a second way of measuring the flattening of our globe.

In 1799, the French astronomers, basing their calculations on the results of work previously done by Bouguer and La Condamine in Peru, Maupertuis in Lapland, and Picard and Cassini in France, found that the entire circumference of the Earth should contain 20,522,960 toises, a toise of six feet being the legal unit at that time in Paris. In taking as a unit a length of $\frac{1}{40,000,000}$ part of the circumference, they thought they would obtain one which would be approximately half a toise and would accordingly not introduce much confusion into current commercial affairs, at the same time having the advantage of being a natural unit of length. This unit, the metre [39.370,113 in.], became the foundation of the metrical system of weights and measures, which is now adopted by all civilised countries.[1] The metre is preserved as the length of a bar of platinum at 0°C. [32° F.] deposited in the archives in Paris; copies of this have been made under the auspices of the International Bureau of Weights and Measures, which is established at Sèvres and are kept by each of the countries adopting the system.

The metre standard was the result of the collection of geodetic measurements that had been

[1] In Great Britain and the United States the metric system is, unfortunately, in use only for scientific purposes.

made up to the period of the beginning of the nineteenth century. At that time, the flattening of the Earth was taken as $\frac{1}{330}$ part. During the last century, more exact measures of meridional arcs have been perfected and multiplied, and it is now established beyond doubt that the terrestrial flattening is $\frac{1}{297}$ part, expressing the denominator by the nearest unit. This being so, the metre standard is somewhat too short, viz., by about $\frac{1}{5}$ of a millimetre [.007,874 in.].

Scientists in general have decided that it would be useless, as this difference is so small, to undertake again the long and tedious experiments which were necessary for the establishment of the original standard; the actual metre, as used internationally, is therefore defined as the length at 0° C. [32° F.] of the particular bar of platinum above described. This decision is both fortunate and wise, for besides avoiding much heavy work, there is a second reason for not attempting a standard exactly based on the Earth's magnitude. As will be shown in the course of the present work, nothing in connection with the Earth is constant, and consequently it would be necessary to be always altering, by a few microns,[1] the absolute value of the unit of length.

[1] A micron is $\frac{1}{1000}$ of a millimetre = .00003937 inch.—*Trans.*

Nevertheless, as every material thing is not everlasting, but perishable, the bar of platinum constituting the standard metre is not indestructible; neither are the copies made from it. So physicists have compared the value of their unit of length with another unit independent of matter, and independent even of the Earth's dimensions. This new unit is the length of a wave of light of a particular colour, measured in vacuo, that is to say, the distance which separates any two consecutive crests of the waves generated in the ether by the vibratory movements which constitute light. To the American physicist, Michelson of Chicago, is due the credit of having first attempted this comparison. He was successful and found, after much difficult work, wonderful because of its precision and the perseverance necessary for its completion, that a metre contained 1,553,163.5 times the length of the wave of the red cadmium light, and 2,083,372 times the blue radiation from the same metal. Thus we are no longer entirely dependent on the standard metre bar of platinum, and our unit is obtainable from one which is indestructible, as it will exist as long as light itself. Clerk Maxwell already realised the importance of a unit independent of the Earth's size when he wrote in the preface of his famous treatise on

electricity: "Such a standard would be independent of any changes in the dimensions of the Earth, and should be adopted by those who expect their writings to be more permanent than that body."

Geodetic measures afford us exact knowledge of the Earth's size, in contradistinction to the experiment mentioned at the beginning of this chapter which gives only an approximate result. Let us begin by understanding that in the determination of the Earth's form no account is taken of the continental protuberances or the oceanic hollows. We will suppose the line of sea-level to be prolonged under the continents and the imaginary surface thus produced, called the geoid, is that whose form we will endeavour to determine. The fluidity of the oceans causes them to obey the laws of attraction and centrifugal force, and mechanics shows that such a surface can only take a flattened figure, which is that of an ellipsoid of revolution.

This ideal surface is not entirely of theoretical use; the operation of levelling consists precisely in finding the height of each point of the land surface above it, that is to say it resolves itself into finding the distance between any point on the Earth's surface and the surface of the sea pro-

longed in imagination beneath it. The mining engineer Lallemand has carried this work to an unlooked-for degree of precision. Now, as will be seen later, the mean altitude of the continents is only 700 metres [3000 ft.], which is scarcely more than $\frac{1}{10,000}$ part of the Earth's radius. Also, the slope of the land towards the sea is in general very slight; the courses of the large rivers give some idea of it. It is, therefore, quite legitimate to take the form of the geoid as that of the Earth itself, except when it is desired to determine the altitude of any land or the depth of the oceanic abysses or when we wish to investigate the local anomalies of the surface.

The results of these measures discussed with so much care by the German geodesist Helmert have led to the adoption of the following values. The semi-major axis of the terrestrial ellipsoid, that is to say the radius of the terrestrial equator, is 6,377,857 metres [3963.125 miles] long. The semi-minor axis, which is the distance from one of the poles to the Earth's centre, is 6,356,606 metres [3949.92 miles] in length. The most probable value of the flattening is $\frac{1}{297}$. The Earth's circumference at the equator is 40,073, 351 metres [24,900 miles].

On account of the flattening, the North Pole

is about 20 kilometres [13 miles] nearer to the Earth's centre than is the equator.

Since we know the dimensions of the terrestrial ellipsoid we can determine its surface and its volume. The total extent of the Earth's surface is 510,082,000 square kilometres [197,000,000 sq. miles]. Of this, the continents and islands occupy 145,000,000 [56,000,000 sq. miles] and the oceans and seas 365,000,000 [141,000,000, sq. miles]. There is not, as will be seen, an equal division into land and water; the latter occupies two and a half times as great a surface as the former.

Not only is there not an equal division as regards the whole Earth, but the distribution of the land is very different in the two hemispheres. If we take as centre of a hemisphere the little Île Dumet, which lies near the mouth of the Vilaine, in Southern Brittany, or, in other words, if we place ourselves sufficiently far from a terrestrial globe, arranging matters so that a line from the eye to the centre of the globe passes through this little island, the hemisphere that will be visible contains exactly as much land surface as water surface (Fig. 6). On the other hand, the hemisphere opposite to this one will be essentially a marine hemisphere, containing, as it does, nine times more water than land surface. Our globe

thus possesses a land hemisphere and a marine hemisphere. Without being so characteristic as the foregoing, the aspect of a terrestrial globe, when the eye is placed in front of that point of the equator which occupies the middle of the Pacific, is also very instructive. An immense stretch of water, the Pacific Ocean, is seen extending over

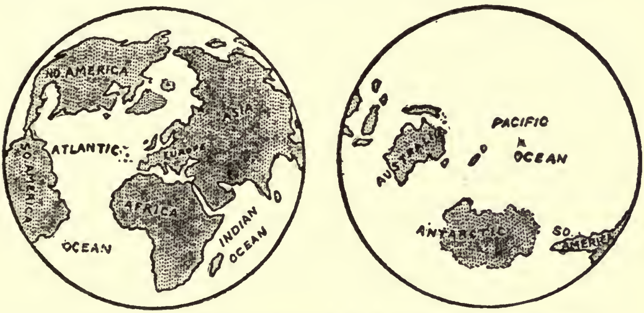



Fig. 6.—Land Hemisphere and Water Hemisphere
(Taking as a pole the Île Dumet.)

nearly a whole hemisphere, while the opposite one contains the greater portion of two continents.

Every point of the Earth has what is called its antipode, that is to say the point which is diametrically opposed to it in the other hemisphere. Now, only $\frac{1}{20}$ of the land surface has an element of land as antipodal point; the other $\frac{19}{20}$ have a point of the sea surface opposite to them. From this there follows a general law, that of the diametrical opposition of the continents and the seas.

As Lapparent has expressed it, there are nineteen chances to one that any element of the land surface will have as antipodal point a part of the Earth's surface which is covered by the sea.

This diametrical opposition of land and water results from the tendency exhibited by the terrestrial crust to take a tetrahedral form at the time of its solidification. This form is that of a pyramid with three equilateral faces, each apex of which is opposite to a face and vice versa. The faces of the tetrahedron are represented by the oceans (*see* Fig. 4, p. 32, *and* Fig. 5B, p. 54), and the apices correspond to the emergent land; consequently there is an opposition between the continents and oceans on the Earth's surface. The examination of a map of the world will confirm this. The land surface, which is in great excess in the Northern Hemisphere, may be subdivided into three chief masses: the European continent, the Asiatic continent with its Australian prolongation, and the American continent. There are also three chief oceans, the Atlantic, Pacific, and Indian oceans.

Furthermore, polar expeditions have furnished additional proof of the diametrical opposition; around the North Pole is the Arctic Ocean with depths of more than 3000 metres [9800 ft.], while

about the South Pole there exists, on the contrary, an antarctic continent of considerable elevation and an extent of the same order as that of Europe. The distribution of lands and seas may, therefore, be considered to conform to the law of diametrical opposition. In the course of Chapter VII., when describing seismic phenomena, we shall return in fuller detail to the tetrahedral theory.

Having studied the Earth's surface we shall now consider the facts relative to its volume.

The volume of the ellipsoid is 1,083,260 millions of cubic kilometres [260,000,000,000 cubic miles], and, in order to give some material idea of what such volume is, we shall state that it would require 340 times the volume of the Great Pyramid of Egypt to equal one cubic kilometre. The Earth is not truly spherical, but is flattened at the poles and bulges at the equator; the volume of this bulge is the $\frac{1}{151}$ part of the total volume of the Earth.

There are, also, other volumes of interest to us besides that of the globe taken as a whole. We may try to evaluate the volume of all the land which rises above sea-level and also the total volume of all the water contained in the oceans. We have already noted the great inequality between the continental and marine surfaces, and

this inequality becomes still greater when we come to examine the relative volumes.

The total volume of the continents above sea-level is about 100 million cubic kilometres and the volume of the water contained in all the seas of the globe is 1300 million cubic kilometres. The volume of the ocean is therefore thirteen times greater than that of the continents.

As a result of the precise measures of altitude and depth, an old and false idea of ancient geographers falls to the ground. They believed that, if the water of the seas were removed and the continents razed down to the sea-level, the debris of the latter would just fill up the oceanic hollows. Nothing could be more untrue. If we imagine a somewhat different operation, that of all the emergent land being formed into a shell of uniform thickness, having the same contours as those of the actual continents, the thickness would be only 700 metres [3000 ft.]. If, however, the same thing were done with the bed of the seas, so that they were all of uniform depth, the contours remaining as at present, the resulting depth of water would be about 3550 metres [2.2 miles]. As this depth is spread over a surface two and a half times greater than that of the land, the mean altitude of which is only a fifth part of the mean depth of the seas,

the difference between the two volumes is very marked.

We have next to consider how the protuberances and hollows which form the relief of the terrestrial crust are distributed on the land surface and the bed of the sea. The imagination of the ancient poets depicted the ocean as a gulf whose depth, which was almost infinite, increased rapidly as the shores were left, ending in abysses inhabited by frightful monsters. Now, soundings have been so universally made that Prince Albert of Monaco has been able to draw up a topographical map of the bed of the oceans just as, and in the same way, the laborious work of the ordnance officers of all countries have enabled detailed maps of the relief of the land surface to be made.

In examining these maps, it is seen that a continent is not a kind of regular dome whose summit occupies the middle part, and also that an ocean is not a kind of funnel whose sides converge towards a central hole. On the contrary, almost all the important mountainous masses are for the greater part of their length situated on the margin of the oceans; for example, the Andes along the Pacific coast, the Alps along the shore of the Mediterranean, and the Scandinavian mountains close to the North Sea. It is just the same with

regard to the marine hollows. The greatest depths are not to be found at the centre of the seas; thus the chief depths of the Pacific are situated in its western part, where the sounding line has descended in several parts below 9000 metres [5.6 miles], and the same holds in the case of the Atlantic, which is deeper at its edges than in the middle, where a long submarine ridge exists.

If the sea were to disappear completely, leaving uncovered that part of the Earth's crust which forms its bed, the attentive observer would not notice any special character suggesting the situation of the former oceans. The bed of the sea has a relief like that of the land surface, and if the higher parts of the latter are more precipitous than the more rounded submarine summits, it is because of the erosive action which exterior agents exercise on the emergent surface, while the oceans protect the irregularities covered by their waters.

Nevertheless, certain general tendencies may be observed on the relief globe which would result if the Earth were deprived of its seas, and these tendencies are so general that they may be formulated into laws. Thus, the accidents of the relief do not have two sides symmetrically inclined towards the lower surrounding regions; they are, on the contrary, unsymmetrical. In the case of

the slopes of an oceanic hollow, or the flanks of a chain of mountains, one side is almost always abrupt and the other a gentle declivity. Furthermore, in most cases, the abrupt slope of a mountain chain bordering an ocean is continuous with the equally abrupt side of a hollow in the ocean bed, so that the mountain thus seems to dip sharply into the sea while the slope of its other side stretches for a long distance with a gentle fall. The Andes constitute the most striking case of this; their summits are 6000 and 7000 metres [3.7 to 4.4 miles] high, and the ridge falls sharply to the Pacific, its steep slope being continued under the sea by a long hollow having depths of 6000, 7000, and 8000 metres [3.7, 4.4, and 5 miles], while the opposite side of the range slopes gently towards the Atlantic until it is lost in the Argentine Pampas.

As has been neatly expressed by Lapparent, the crust of the Earth as a whole resembles an old patchwork whose parts have shifted with respect to each other, and in the places where the great folds are produced, such as that which gave rise to the Andes, it is as if the crust, being no longer sustained below at all its parts by the contracting nucleus, had acted as does a piece of material, which is too large, that is to say formed a fold,

the sides of which after a sudden descent merge into the general level.

There is one characteristic fact: these folds, the irregularities of the surface, seem to run in lines. A number of such alignments may be seen on the map of the world: the Ural Mountains, the Andes, the oceanic hollows of Polynesia. The islands which fringe the Pacific clearly demonstrate this tendency.

Knowing its dimensions, it remains to deal now with the Earth's mass. It is to be noted that we speak of the mass and not the weight of the Earth. The idea of mass requires to be carefully explained and is quite different from that of weight. The mass of a body is the quantity of matter it contains, whatever the exterior form under which the said matter is revealed to us. If the body be at rest, this quantity of matter remains in that state by reason of its inertia; if, on the other hand, a given force acts on the body tending to displace it and to impress any movement whatever upon it, the resulting motion will the less readily take place in proportion as the mass is greater. Poisson has well stated this idea of mass in saying: Mass is the coefficient of resistance to motion.

The mass of a given body is thus a constant quantity. Its weight, on the contrary, which is the force with which it is attracted by the Earth,

varies in proportion as the body is moved either horizontally, from one place to another, or vertically. It should be noted that, as the attraction of the Earth exercised upon objects at or above its surface is the cause of weight, the Earth itself, as a whole, can have no weight in the strict sense of the word. It cannot attract itself. The Earth has weight with respect to the Sun, but has no weight in the sense in which the word is used for the bodies on its own surface. The evaluation of its mass is therefore the only question concerning us.

It will be remembered that the mass of a gramme [15.432 grains] has been taken as a scientific unit. Now, forces cannot be expressed in grammes but have to be referred to a special unit, called the dyne, a dyne being the force which when applied to a body of mass one gramme gives to it a uniform acceleration of one centimetre [.3937 inch] per second.

In order to measure the total mass of the Earth, an experiment, based on the Newtonian law of attraction, is made. Two bodies are chosen, one movable and of small mass, the other fixed and of considerable mass. It is essential to use methods of measurement which are sufficiently sensitive to show the displacement which the small body

suffers under the attractive force of the known mass of the greater one. The displacement being known, we are able to exert an opposing force on the small body which neutralises it and whose measure gives us that of the attractive force.

We may use as the large attracting mass either a natural mass such as that of a mountain, or a selected mass for use in the laboratory. There are thus two distinct methods, the geographical and the physical one.

The attraction exercised by a mountain on a body of small mass placed in its neighbourhood can be measured in two quite different ways. The first is by the observation of the swing of a pendulum upon the summit of the mountain. Since the pendulum is thus at an elevation the action of gravity upon it is feebler and the amount of such action may easily be calculated when the height of the summit is known. Now, it is found that the swing thus calculated is not the same as the swing actually observed; there is a perturbing action due to the presence of the mountain, which acts contrary to the diminution of gravity due to altitude alone. The difference between the calculated and observed times of swing thus enables us to determine the attractive action of the mountain; this is the dynamic method.

The second is a static method. Let us suppose that the density of the mountain is known by reason of the work of geologists, and the position of its centre of gravity exactly determined by precise topographical operations. If we take up a position to the north of the mountain, and there set up a plumb line, it will be slightly deviated, the suspended mass being attracted towards the centre of gravity of the mountain by the mass of the latter. Produced to intersect the celestial sphere, the plumb line would not meet it at the same point as if the mountain did not exist, but in one more to the north. Similarly a plumb line placed at the south of the mountain would also be attracted by it, and the line if prolonged would meet the celestial sphere at a point to the south of that at which it would have done so if the mountain had not attracted the suspended mass.

FIG. 7.—Deviation of a Plumb Line by a Mountain.

In other words, these two plumb lines would be directed, if the mountain did not exist, along two of the radii of the Earth and so would intersect at its centre. In the presence of the mountain both are deviated towards

each other and, if prolonged, would intersect at a point nearer the Earth's surface than its centre (Fig 7). If there were no deviation, the angle made by the two plumb lines produced, would be equal to that between the verticals at the given points of observation, that is to say, equal to the actual difference of latitude between the two stations. When deviation is caused by the mountain the two lines make an angle greater than the latitude difference. If this angle can be determined we should be able to calculate the attraction exerted by the mountain on the small suspended masses.

Now, this angle may be obtained astronomically. All that is necessary is to find, by observation of a star, the altitude of the pole above the plane of the horizon for each of the two stations, the horizon being defined as the plane exactly perpendicular to the plumb line in question. The real difference of latitude, on the other hand, may be measured by finding the distance between the two places by means of topographical operations. The observed, or apparent, difference may thus be compared with the real one and hence twice the angle of the required deviation, caused by the mountain, deduced.

Such is the principle of the geographical method.

It is obvious that any other natural mass may be made use of as the attracting body, provided its mass can be exactly determined. This is, however, the weak point in the method, at least as far as mountains are concerned; their mean density is always uncertain, for the disposition of the rocks and minerals composing them is not precisely known. As a result there is an uncertainty not only as to the value of the attracting mass, but also concerning the exact position of the centre of gravity. Nevertheless such methods were the first ones made use of; Bouguer and La Condamine, in 1736, determined the deviation exerted on the plumb line by the mass of Chimborazo in Peru, and found the sum of the angular deviations on the north and south of the mountain to be 19 seconds of arc. In 1774, Maskelyne repeated this experiment in Scotland, studying the deviation from the vertical caused by the mountain Schiehallion. Two stations were chosen to the north and south of the mountain, respectively, and topographical operation gave 43 seconds as the real difference of latitude of the two places; the same difference measured astronomically was found to be 54.5 seconds. The discrepancy therefore was 11.5 seconds, due to the sum of the angular deviations exerted on the two plumb lines by the attraction

of the mountain. At the same time, the geologist Hutton had studied the composition of the mountains and had estimated its volume as precisely as possible; this operation alone took more than three years.

As a direct result of such an experiment, we find the intensity with which a mountain of known mass deviates a suspended mass from the vertical, at a distance from its centre of gravity. This small mass may be weighed on a balance; we then know with what intensity the earth (supposedly spherical) attracts towards its centre a mass situated at a point of its surface, at a distance from the centre equal to the radius of the Earth.

The ratio of the values of the attractive forces gives the ratio of the attracting masses in the two cases. The value of the Earth's mass may, therefore, be deduced from that of the mountain. Also, mass is the product of volume and density, and the Earth's volume is known from the geodetic operations which give its dimensions. Therefore, if we divide the mass by the volume, we obtain the mean density of the globe. This density may thus be imagined: Let us suppose the whole Earth to be ground to powder in a gigantic mortar and the powder subsequently mixed and stirred in-

timately together; a substance would be obtained whose density, that is to say mass per unit volume, would be the mean density of the Earth.

Experiments analogous to those of Maskelyne have shown that this mean density is approximately equal to 5.5.[1]

We shall see later how important this result is with reference to our knowledge of the internal structure of our globe.

The physical methods for the determination of the Earth's density are susceptible of a much higher precision, and can be carried out in a laboratory. To Cavendish is due the credit of having designed the first apparatus of this kind and having made, as Joseph Bertrand has said, "a balance to weigh the Earth."

The attractive forces exercised by one portion of matter on another are very feeble, and the reason the force of gravity is so great is only because the mass of the Earth is relatively so large. We shall now see how the value of the attractive force between two masses each equal to unity can be found. Since the force is very slight, it is necessary to make use of an opposing force, also very small, to counterbalance it. For this

[1] The standard of density (= 1) is that of water at a temperature of 4° C. [39.2° F.].—*Ed.*

purpose Cavendish chose the torsion or twist of a long, fine wire (Fig. 8).

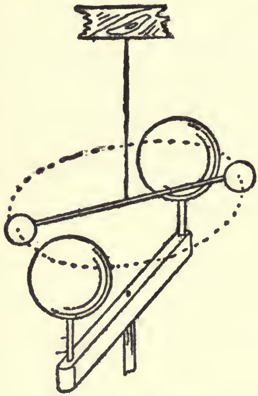


FIG. 8.—Cavendish's Experiment.

He fixed two small leaden balls of known equal mass at the extremities of a very light lever which was suspended at its mid-point by a silver wire. The lever, therefore, pointed in a fixed direction dependent on the position in which the wire was free from strain. Two large fixed leaden balls of known mass were introduced, as shown, to the right of the movable ones (the right being that on the right hand when looking from either of the small balls towards the wire). Each of the large balls attracted the small one near it, and their added effect tended to turn the lever so as to bring the small balls up to them. But this motion was opposed by the torsion or twist of the wire, the value of which had been carefully determined by preliminary experiments. The angle through which the lever actually turned before it was brought to rest by the opposing force thus served to measure the value of the force which balances

the attraction between the balls, and, this being exerted between known masses at known distances, was thus fully established by experiment. The whole apparatus was placed under cover so as to guard against disturbing air currents.

Besides the equilibrium method, Cavendish also employed a dynamical method which consisted in studying the oscillations of the lever deviated from its normal position by the attraction of the large balls and brought back towards this position by the torsion of the wire, which made it oscillate similarly to a pendulum. This attraction, compared to that of the Earth on the seconds pendulum, gives the ratio of the density of lead to the mean density of the Earth; the average result of twenty-nine determinations has given 5.48 as the required mean density, that of water being taken as unity.

This experiment has been repeated under the most diverse forms; Cavendish's apparatus has been modified in accordance with all the progress that has since been achieved in the construction of physical instruments and also in the methods of observation. But these measurements, some of which have been made by illustrious physicists such as Baron Eötvös, Cornu, Baille, Poynting, etc., have only confirmed the mean value 5.5

found by Cavendish, in spite of the greater delicacy of the experiments. This illustrates the fact, demonstrated by the history of all science, that the man who first discovers a phenomenon, devises a method and makes an apparatus for measuring it, determines at once the true value of the measure. He makes up for the instrumental deficiency by that particular intuition which constitutes the essence of genius. If we consider the great quantitative determinations of the laws of physics, *e. g.*, the mechanical equivalent of heat, the velocity of light, the latent heat of fusion of ice, etc., in every case the later results, more and more precise, have only confirmed the figures obtained by him, who, in each case, may justly be called the first.

We, therefore, know the Earth's mean density, from which it follows that its mass, compared to the mass (*not the weight*) of a kilogram, is 6,100,000,000,000,000,000,000,000 [3,716 *quintillions of tons*] or as modern physicists would write it $6.1 \times 10^{24}$ kilograms. The imagination can hardly picture such a mass, and yet it is a very small one in comparison with the masses of some of the celestial bodies.

One result of these determinations is that we can calculate the force with which two known

masses, placed at a known distance apart, attract each other.

Newton's law tells us that any two bodies whatsoever attract each other with a force directly proportional to the product of their masses and inversely proportional to the square of the distance which separates them. This law may be expressed by a very simple formula; the intensity of the force is obtained by multiplying together the masses of the two bodies, expressed in grams [15.432 gr.] and dividing the product by the square of the distance apart, expressed in centimetres [.3937 in.], the whole being multiplied by a coefficient which denotes the proportionality.[1] This coefficient, which is the constant of gravitation, is not an abstract number but has, on the contrary, a very distinct physical significance. It represents the intensity of the force of attraction between two masses, each of one gram, a centimetre apart. The coefficient is very small; it is denoted by the letter k, and its numerical value equals $\frac{6.5}{100,000,000}$ *i. e.*, $k=6.5\times 10^{-8}$.

This force is expressed in units of force, that is to say, in dynes, the gram being the unit of mass. A dyne is the force which gives an acceleration of

[1] The formula of Newton's Law is $f=k\frac{mm'}{d^2}$ where m,m′ are the masses of the two bodies concerned and d the distance.

one centimetre per second to the mass of one gram. If the force of gravity instead of the dyne acted on this mass, the acceleration produced would be 981 centimetres [32 ft. 2.2 in.] per second at Paris, as measured by pendulum experiments. Consequently a dyne represents the 981st part of the weight of a gram; it is a force of sensibly the same power as that exerted by the weight of a milligram [.015432 gr.].

We can now easily calculate the force between any two given bodies. If we wish, for example, to find that exerted by a sphere of lead, 10 metres in diameter [33 ft. 9.7 in.], on a spherical mass of one kilogram [2 lbs. 3.27 ozs.], also of lead, whose diameter is 2 decimetres [7.874 in.], the result is a force which, compared to the weight of a gram [15.432 gr.], is not quite half a milligram [.007716 gr.]. It is, therefore, the enormous mass of the celestial bodies to which the importance of the attractive forces between them is due. And the forces are, of course, greatly diminished by reason of the vast distances separating the bodies, especially as it is the square of the distance which comes into the formula.

The knowledge of the Earth's mean density, which Cavendish and his successors have shown to be equal to 5.5, leads to a conclusion of the

highest importance relative to the constitution of the interior of our globe. The density of the rocky strata which constitute the Earth's superficial crust never greatly exceeds the mean value 2.5. In order, therefore, for the Earth to have a mean density of 5.5, the density of the interior must have a much greater value in order to compensate for the relative lightness of the outer layers.

Roche and Wiechert have made a study of this question and have deduced the law which bears their joint names, the law of Roche–Wiechert. The Earth is composed of a nucleus of which the density is about 10 and whose diameter is eight-tenths of that of the whole globe; this nucleus is surrounded by a spherical layer of lesser density. As only metals have densities as high as 10, we must suppose the central mass of the Earth to be composed of metallic matter. Furthermore the electrical and magnetic phenomena of which the Earth is the seat and the constitution of the lavas thrown out from volcanoes show that this metallic nucleus is largely composed of iron.

We have next to consider in what state such dense metallic matter exists in the Earth's central portion. Every time that we penetrate into the Earth's interior, for example, on descending the

shaft of a very deep mine, we find a continuous increase of temperature as the depth below the surface increases. Such increase is usually proportional to the depth, when the same stratum is concerned and its mean value, called the geothermic degree is 1° C. [1.8° F.] for 33 metres [108.5 ft.] depth, that is about 3° C. [5.4° F.] per 100 metres [328.5 ft.], 30° C. [54° F.] per kilometre [.62 mile], or 3000° C. [5400° F.] for 100 kilometres [62 miles].[1] Therefore, if the terrestrial crust was only 100 kilometres in thickness the strata at that depth would exist at a temperature of 3000° C. [5400° F.], which is high enough to melt and vaporise all known bodies. We may remark here that the Earth's shell does not attain such a thickness as this; the actual thickness of the solid crust surrounding the nucleus is not more than 70 kilometres [43.5 miles]. In proportion to its diameter, the terrestrial crust is much thinner than the shell of an egg.

Metals, therefore, in a state of fusion constitute the magma which forms the central mass of our globe. The immense pressures to which they are subjected must not be forgotten; these pressures

[1] At an increase, in other words, of about 1° F. for every 60 ft.—*Ed.*

reach and surpass that of millions of atmospheres. It is quite impossible to represent to the mind, even with the help of Amagat's results, the state in which a body exists when subjected at the same time to such a high temperature and great pressure. Doubtless the mass is of a consistency practically equivalent to the solid state. It would only be in the immediate neighbourhood of the solid crust, just below it, that the outer layers of the central mass, not subjected to such great pressures as those deeper down, could exist in the fluid state, constituting the molten matter which volcanoes in eruption eject.

These liquid masses must exhibit the phenomenon of convection currents which mix them together and agitate them, and which communicate their impulses to the crust above. How are they produced, these perpetual movements, which are a manifestation of the incessant "life" of the Earth? Is the enclosing crust itself stable, or subject to continual vicissitudes? The study of luni-solar action, of the "tides" of the crust, and of the shocks to which it is subjected will enable us to answer these questions.

# CHAPTER IV

## THE MOVEMENTS OF THE EARTH

WE have passed in imagination the birth and youth of the Earth, and the evolution of its adolescence. We have also learned its form and dimensions. It is now time to endeavour to find out in what way it lives, to speak figuratively, and in what way it is evolving in the actual present. Possibly also with this knowledge we may be able to foresee what will happen to it in future ages.

The primary manifestation of life is movement, so that we will first study the movements of the Earth. These movements are numerous and some are very complex, but there are two chief ones, the movement of rotation and the movement of translation.

The Earth turns on itself; it rotates round a line, an ideal axis, which is called the line of the poles, and which is nearly, but not quite, fixed with regard to the terrestrial spheroid; the poles

are the points where this axis, if real, would cut the rotating surface of the geoid at a given time.

All our measurement of time is based on this movement of rotation, which governs the length of the day.[1]

The angular velocity of the Earth, which is the angle through which it turns during a unit of time, is not very great. A radius to the Earth's centre at the equator sweeps out a sector of only 15° in the course of an hour. But, in spite of the small angular velocity, the circumferential velocities are considerable. Thus a point on the equator moves 465 metres [1525 ft.] every second because of the Earth's rotation. This almost equals the initial velocity of the bullets of the old infantry rifle 1874 pattern, called the Gras rifle. At a latitude nearer the pole, the velocity decreases markedly; at Paris, it is, however, still considerable, as will be judged from the fact that as I write these lines I am carried along with a velocity of

[1] The *true solar* day varies in the course of a year as much as 31 minutes; for this reason the standard day is determined by the *average* time between solar noons, being called the *mean solar* day, which is always 24 hours in length. The true rotation time of the Earth, however, is 23 h. 56 m. 4.09 s. This is known as the *sidereal day*. Because of the Earth's revolution about the Sun, the former must on the average make slightly more than one rotation to bring the Sun again on the meridian. This extra part of a rotation takes 3 m. 56 s.—*Ed.*

365 metres [1213 ft.] per second. This equals the initial velocity of the bullet of a service pattern revolver.

The discovery of the Earth's rotation forms a noble page in the history of the conquests of the human mind. Rational deductions led Copernicus and Galileo[1] to this conclusion, and we are well aware of the storm which the announcement of the fact produced. Little by little, the discoveries made by astronomers added unforeseen knowledge which raised to the level of absolute certainty what many minds still wished to treat as a supposition.

For example, Newton's law necessitates that a celestial body describing a closed orbit around a fixed point must be attracted by a force acting from that point. Such attraction implies a mass concentrated at this point, that is to say another body, since volume is inseparable from mass. Consequently if the stars rotate around the polar axis of the immovable Earth, the line round which they appear to describe circular orbits, it follows

[1] In the 5th century B.C., some of the Greek nature philosophers, notably Pythagoras, Democritus, and Heraclitus, evolved the essentials of the theory revived by Copernicus and bearing his name. Their theories, however, were not accepted by the majority of their contemporaries and were later totally abandoned for the false Ptolemaic theory.—*Ed.*

that an attracting body must lie in the centre of each such orbit, one for every star. There would, therefore, be a succession of celestial bodies, all of large mass, showing an alignment along the Earth's axis produced. Astronomers have never observed any such alignment, which could not have remained unnoticed.

Furthermore, observation has made it quite certain that the Earth is one of the planets belonging to the Solar System. It is an established fact that all these planets rotate on their axes and there is no reason why the Earth should be the only exception to the common law, particularly as it is by no means the largest or most massive one.

In the middle of the nineteenth century, Foucault furnished direct experimental proofs of the Earth's rotation by his two experiments, the great pendulum in the Pantheon at Paris and the gyroscope.

Starting with the knowledge, capable of experimental proof, that a pendulum swings in a fixed, unchanging plane whatever movement its point of support undergoes, Foucault in 1851 attached a wire 70 metres [229 ft. ] long to the keystone of the dome of the Pantheon. This wire carried a ball weighing 18 kilograms [39.75 lbs.], below

which was fixed a pointed style; the whole thus formed a long pendulum, oscillating very slowly. At the extremity of each swing, the style of the pendulum cut through a heap of sand placed near the farthest point it reached. In order to start the oscillation without introducing any extraneous movement, the ball was pulled to one side and fastened to a fixed support by a thread which was subsequently burnt; the pendulum then began to swing freely. Now, at every oscillation the breach made in the pile of sand was observed to widen, in the direction to the left of an observer looking at it from the far side. As it was known that the plane of swing was invariable, and constituted a fixed reference direction, the experiment showed that the support was being displaced. In other words, the Pantheon, and consequently the whole Earth itself, was rotating in a contrary way to that in which the breach was widened.[1]

Foucault wished to do still more, and he succeeded. He invented the gyroscope. Imagine a series of pendulums side by side all of equal length, all carrying identical masses and swinging about

[1] In 1902 on the occasion of the 50th anniversary of this demonstration, Foucault's experiment was formally repeated in the Pantheon, in the presence of the chief State officials, under the same conditions as when originally made. The author of this work had charge of the experiment.

the same axis, but, instead of describing only the arc of the circle, let them be supposed to complete the entire circle, all swinging in the same plane, perpendicular to the common axis of rotation. A gyroscope, which is actually a heavy flywheel of small radius turning very rapidly around its axis, would act similarly to such a series, and so should maintain an invariable direction. If one of the points of the Cardan suspension of this instrument be observed by means of a view-telescope it will appear to move in the opposite way to the Earth's rotation, which latter is thus once more demonstrated.

The applications of gyroscopic action that have already been made are well known. Sailors have utilised it to give a fixed horizon when a distant fog hides the sea horizon, it being unaffected by the movement of the ship. It is proposed to make use of it, also, instead of the magnetic needle to give the true north, and aviators have attempted to utilise it for rendering their machines more stable.[1]

When Foucault's experiment is attentively observed, not only qualitatively, but also quanti-

[1] As this English translation goes to press the newspapers are reporting a successful gyroscopic stabiliser for aeroplanes.—*Ed.*

tatively, if the expression may be used, one is struck by a fact which, at first sight, seems inexplicable and contradictory but which has really quite a simple explanation.

If the angle through which the plane of oscillation of the pendulum seems to turn, for example, during one hour, be measured, it is found that its value corresponds at Paris to a velocity of rotation of one complete turn in 36 hours. Now, it is quite certain that the Earth's angular velocity is one rotation in 24 hours [23 h. 56 m. 4 s.], since it is this velocity which gives us the definition of the unit of time, a day, and its subdivision, an hour. There is thus an apparent paradox. The reason is that the pendulum experiment shows the rotation, not around the line of the poles but around the vertical line at the place of observation, in this case the vertical to the surface at Paris. In order to find the velocity of rotation with reference to this vertical we must multiply the actual velocity by the sine of the angle of latitude of the place of experiment. If this calculation be made for the latitude of Paris it is found that the apparent velocity of rotation of the plane of swing of the pendulum or of the gyroscope is exactly one turn in thirty-six hours.

As a consequence of this, if the experiment be

made in gradually increasing latitudes, that is going northwards, the velocity of rotation will increase, and at the pole itself, where the Earth's axis and the vertical at the place coincide, the pendulum would appear to describe one turn in twenty-four hours [23 h. 56 m. 4 s.—*Ed.*]. Arctic or Antarctic explorers who have the good fortune to reach the actual pole, and who can stay there long enough to study such phenomena, would find this a most interesting experiment to try. In proportion as the equator is approached, on the other hand, the velocity with which the pendulum appears to turn becomes smaller and smaller until at the equator itself, the pendulum oscillates in a constant direction. This has been tested by experiment. In the southern hemisphere the phenomena are identical, but the apparent motion is in the opposite direction.

The scientific value of Foucault's experiment is considerable. Thus if the apparent velocity of rotation of a gyroscopic apparatus be measured with care, the latitude of the place can be deduced. Now the latitude, defined astronomically, has not been hitherto obtainable save by the observation of stars, that is to say, by means of celestial reference points. Foucault's method requires neither a view of the sky nor observation of stars and, by

using it, an astronomically defined co-ordinate may be determined at the bottom of a vault or other place from which no part of the heavens is visible.

If it should become possible to arrange an apparatus enabling this experiment to be made with sufficient precision on board a ship in motion, an important problem will have been solved, for sailors would thus be able to take their reckoning even when the Sun or stars were hidden by fog or clouds.

The practical consequences of the Earth's rotation are of supreme importance, and it may be said that the essential features of the system of atmospheric circulation, and also, in part, those of the oceanic circulation, result therefrom.

The science of mechanics shows that, as a consequence of the theorem of Coriolis, any moving body on a sphere rotating upon its axis, as the Earth does, is by reason of this rotation deviated in a direction to the right of its path in the northern hemisphere and to the left in the southern hemisphere. Accordingly when we have to study the great movements of translation, whether of the gaseous masses which constitute the atmosphere, or of the liquid masses forming the oceans, it will be necessary to take account of the permanent action of that deviating force.

This deviating force is, nevertheless, very feeble. We know by mechanics that it is proportional to the angular velocity of the rotating sphere, to the mass of the body moving on the surface of the sphere, to the linear velocity of this body, and also to the sine of the latitude. For a body of mass one gram [15.432 gr.] moving with a velocity of one metre [39.37 in.] per second at the latitude of 45° it would be about $\frac{1}{100,000}$ part of the weight of the body (to be exact $\frac{1}{98,000}$ part). But this force acts on considerable masses, moving with large velocities over long distances, and, therefore, it is not surprising that it exerts a marked action upon the paths of the fluid masses which circulate around the solid crust of the Earth.

Another consequence of the deviating force exerted upon moving bodies is shown in the eastward deviation suffered by heavy masses falling freely towards the Earth's surface. This deviation is caused by the fact that the linear velocity of the elevated point from which the body commences to fall is greater than that of the point where it strikes the Earth, since the former is farther from, and the latter nearer to, the axis of rotation. The body therefore falls at a point advanced towards the east.

This deviation may be calculated by the prin-

ciples of mechanics; it is very slight. If the calculation be made for the equator where the linear velocities of rotation are greatest, it is found that a body falling from a height of 100 metres [326.5 ft.] will be deviated 33 millimetres [3.93 in.] towards the east. The extreme smallness of this deviation has always hindered the conclusive proof of the phenomenon, the existence and magnitude of which are however indisputable.

We must now consider another result of the Earth's rotation. The movement brings into play a centrifugal force which is greater in proportion as the point of the surface in question is farther from the axis. At the equator, therefore, this force attains its maximum; it tends to neutralise the force of gravity, which it actually diminishes by $\frac{1}{289}$ part of the total value. In other words, at the equator, the centrifugal force is $\frac{1}{289}$ of the force of gravity.

As the centrifugal force is proportional to the square of the angular velocity of the rotating body, and since 289 is the square of 17, it will be seen that, if the Earth were to turn 17 times more rapidly than at present, the force of gravity would at the equator be exactly counterbalanced by the centrifugal force, and hence nothing there would have any apparent weight.

The consequence of such a state of affairs would be disastrous as regards the living beings on the Earth. In the first place, our bodies would weigh nothing and exercise no pressure on the ground, and hence no friction; walking and running would be rendered impossible, as also would be the movement of railway trains over their rails which they would not grip. A jump, the result of a spring given by muscular effort, would carry a person to an enormous height, which would only be limited by the resistance of air, if the air could exist in the circumstances, but probably neither air nor water could remain at the Earth's surface. As regards liquids, they would no longer collect in the bottom of their receptacles; the oceans, driven by the winds, would accumulate on their shores forming mountains of water, which would not tend to fall back again and become horizontal sheets. It would not be possible to pour wine or water into glasses and they would not even flow out of their bottles.

All manual trades would be rendered impossible as their fundamental instrument, the hammer, would not do its work, on account of the disappearance of its weight. No body would fall; there would thus be no indication of the vertical direction by a plumb line or of the horizontal by a level.

Similar remarks could be multiplied to show how impossible existence would be under these fortunately only imaginary conditions.

Independently of its movement of rotation around the polar axis, the Earth has a movement of translation, viz., its revolution around the Sun. This motion takes place in conformity with Kepler's laws, that is to say the Earth's centre[1] describes an ellipse, one focus of which is occupied by the Sun. Our planet does not move in its orbit with uniform velocity; the second law of Kepler, which deals with the areas swept out during equal periods of time states that the Earth moves quickest in its orbit when at its nearest point to the Sun and slowest when at the farthest point.

The major axis of this elliptical path, the projection of which on the celestial sphere is called the ecliptic, has a length of 297,500,000 kilometres [185,450,000 miles] and the eccentricity of the ellipse is about $\frac{1}{60}$. The mean distance of the Earth from the Sun is therefore 148,000,000 kilometres [93,000,000 miles], which is rather more than 23,000 times the radius of the Earth.

The orbit is traversed by the centre of our globe in one year and the total length of this yearly path

[1] Strictly speaking it is the centre of gravity of the Earth-Moon system which describes this elliptical orbit.—*Ed.*

equals 930,000,900 kilometres [577,000,000 miles]. This corresponds to a mean velocity of 106,000 kilometres [66,000 miles] per hour, a speed far beyond the dreams of even the most ambitious of our motorists or aviators.

But the Earth does not always travel with this mean velocity; in accordance with Kepler's second law it moves sometimes more quickly and sometimes less quickly. It will be interesting to give the extreme velocities and to express them not in kilometres per hour but in metres per second. At the period of the summer solstice, when the Earth is farthest from the Sun and consequently moves most slowly, it passes over 28,900 metres [17.9 miles] per second, while about January 1st its velocity is 30,000 [18.6 miles] metres in the same interval of time. No projectile attains a speed comparable to this; the bullets of the most rapid rifles, using a powder such as cordite, scarcely attain a speed of a thousand metres [3,200 ft.] per second. This is very different from the Earth's velocity of translation, with which the reader is carried while he reads this page, a velocity which he cannot suspect because of the total lack of any points or objects near the Earth by which to gauge the movement.

We shall now consider how the two movements,

rotation and revolution, are combined. The first illustration that may be given is that of a rolling ball, moving forward around an elliptical railway; while traversing the ellipse it also rotates upon itself, and, during one rotation, it progresses over the rails a distance equal to the circumference of one of its great circles.[1]

But, in order for this simple combination of the movements to take place, there must be a suitable relation between the velocity of rotation and that of revolution. In the case of the Earth, the velocity of rotation is only $\frac{1}{67}$ part of that of revolution. If we wish to represent the Earth's double movement in one place by that of a ball, we must, therefore, imagine that the ball not only rolls, but also slides at the same time, in such a way as to turn on its axis only once in twenty-four hours.

The game of billiards naturally suggests the idea that it might be possible to demonstrate the Earth's movements on a table assumed to be frictionless.

If we admit that the double movement of the Earth is the result of the impulse of some cosmic force (which is a quite gratuitous hypothesis, a purely mental speculation) it can easily be calcu-

[1] A great circle is the maximum circumference of a sphere.—*Trans.*

lated that such a force could not have been directed towards the Earth's centre, but towards a point situated to one side of it, on the radius perpendicular to the direction of the force, distant about 33,750 metres [20 miles] from the centre, which quantity is $\frac{1}{189}$ of the radius.

If, therefore, we wish to represent the Earth's motion on a billiard table, we must take a ball of 189 millimetres [7.37 in.] radius, that is to say, 37.8 centimetres [14.7 in.] in diameter. The material of which the ball is made should be formed in concentric layers of the same densities as, and proportional in thickness to, the corresponding ones of our globe. Then we must take a perfectly straight cue and hit the ball eccentrically in such a way that, at the moment of striking, the direction of the cue passes through a point a millimetre [.03937 in.] from the centre. The ball will then have a combined movement of rotation and revolution, the velocities of which component movements will be in the same ratio as the actual corresponding ones of the Earth.

Finally, it may be remarked that, during the kind of waltzing movement that our planet performs around the Sun, the polar axis is not perpendicular to the plane of the orbit. It is not upright, but inclined to the ecliptic, in such a way that the

plane of the terrestrial equator and that of the ecliptic make an angle of about $23\frac{1}{2}°$ with one another. The polar axis, therefore, makes the angle complementary to this, viz., $66\frac{1}{2}°$, with the plane of the Earth's orbit. This axial inclination is of primary importance in connection with the life existing on the Earth; it is the reason of the inequality of the days and nights, and it is also the cause of the seasons which succeed one another during the course of a year.

If the Earth were absolutely spherical, and not accompanied by its satellite, the Moon, the movements above described would be the only ones that our planet would experience. But the Earth is not spherical, and in addition to this, it has a satellite revolving round it. Consequently other movements are also imposed upon the Earth. The non-sphericity takes, as we have said, the form of a polar flattening and an equatorial bulge. The effect of the latter is very important. When it is desired to find the attraction exerted by a given mass on a body, one can make the calculation as if all the mass of the body was accumulated at its centre, provided it be spherical and homogeneous. The problem is thus simplified and the result absolutely accurate. But the equatorial bulge renders the Earth not truly spherical, and,

therefore, the attractive forces exerted on it by neighbouring celestial bodies are unsymmetrical excepting in the case where such bodies are situated on the line of the Earth's poles or in the plane of its equator. Save in these two special cases, a neighbouring body, such as the Moon or the Sun, will be at differing distances from the two halves of the equatorial bulge and therefore attract them in different degrees. Consequently the effect will be a tendency to turn the Earth over.

The Moon and the Sun both exert an appreciable effect of this kind. In spite of the small mass of the former, only $\frac{1}{80}$th part of that of the Earth, it produces the larger effect on account of its proximity, its distance from the centre of the Earth being only thirty times the Earth's diameter. On the other hand the Sun is a very great distance away, viz., 11,500 terrestrial diameters, and in accordance with the law of gravitation the attractive force is inversely as the square of this distance. This is partially compensated for by the enormous mass of the Sun, which is 324,000 times greater than that of our planet.

Thus the Sun, in virtue of its great mass, and the Moon by reason of its nearness, continuously act together to change the direction of the axis around which the Earth's rotation takes place.

The line of the poles makes an angle of $23\frac{1}{2}°$ with the perpendicular to the plane of the ecliptic; under the influence of the luni-solar attraction, the former performs a slow rotatory movement, from east to west, in such a way as to describe a cone, the apex of which is at the Earth's centre. The cone is described once in about 26,000 years, after which the terrestrial axis repeats the same successive positions in the next period of 26,000 years and so on. Thus the Earth while turning rapidly around its axis executes a supplementary movement, resulting in the conical displacement of that axis; nothing could better illustrate this than a top which while it spins quickly about its axis slowly describes a cone whose apex is at its point.

The precession of the equinoxes is the name given to the movement executed by the Earth's axis during every 26,000 years. It has important results, from the point of view of the life on the globe. In the course of ages precession changes the relative duration of the seasons, and thus produces secular variations of the general climatic conditions.[1]

The cone-shaped figure described by the line

[1] A secular variation is a progressive or permanent change from the average condition.—*Trans.*

of the poles is not in itself quite regular; its edge is not truly circular but serrated or wavy, somewhat like the cardboard in which fragile objects are packed. The explanation of this fact is as follows: Astronomers teach us that the plane of the lunar orbit suffers a periodical displacement, and that its point of intersection with the plane of the Earth's orbit moves from east to west, performing a complete revolution in 18½ years. During this period the Earth's polar axis is slightly displaced, sometimes interior to and sometimes exterior to, the theoretical conical surface that it should describe in accordance with the phenomenon of precession. As a consequence, the projection of the axis on the celestial sphere describes in 18½ years a little ellipse whose axes have the angular measurement of 36 and 18 seconds of arc respectively. This phenomenon is called nutation.

This does not exhaust the list of the Earth's motions. In its apparent movement round the Earth, the Sun every six months seems to cross from one side of the equator to the other as it passes through the equinoxes. In the precise language of astronomers and sailors, its declination changes sign. In consequence of the equatorial protuberance, the part of which turned towards the

Sun is more strongly attracted than the other part, the projection of the terrestrial axis on the celestial sphere oscillates around a small ellipse whose centre is always situated on the undulated curve arising from precession and nutation, and whose angular dimensions are respectively 2 seconds and 1 second of arc. Thus the serrations due to nutation are themselves serrated by this phenomenon, the period of which is six months.

Furthermore the Moon passes every fourteen days from one side of the equator to the other and this produces a fourth oscillation of the terrestrial axis which describes a fourth very small ellipse, the centre of which remains on the circumference of the preceding one, but whose angular dimensions are only four-tenths and two-tenths of a second of arc respectively.

If we therefore try to summarise all these perturbations affecting the rotatory movement of the Earth, we arrive at the following law: If the terrestrial polar axis be produced until it meets the imaginary spherical surface representing the heavens, a surface which is frequently made use of in astronomical reasoning and which is called the celestial sphere, the line so prolonged does not meet it in a fixed point, even when the revolution of the Earth round the Sun, and its movement in

space, are not taken into account. Every fourteen days it describes a very small ellipse, the centre of which moves in six months around a second and rather smaller ellipse, caused by the displacement of the Sun in declination. The centre of this latter ellipse moves in a third and much larger ellipse, every 18½ years, viz., that of nutation, while finally the centre of this large ellipse in 26,000 years traverses the circumference of the circle due to the precession of the equinoxes. The curve that truly represents the Earth's movement of rotation is therefore one with four combined sets of serrations or indentations.

We may now put to ourselves a new question. Does the Earth's polar axis, although describing a curve of great complexity on the celestial sphere, remain absolutely fixed with reference to the terrestrial crust? In other words, does the actual pole of the Earth remain fixed relatively to the surface? The answer is in the negative. The pole is not so fixed; it moves slowly over the solid crust, the range of movement being however very small, though continual. If the Earth be represented by a wooden ball turning upon an axis of steel, it is as if this axis shook about slightly, instead of being firmly fixed inside the ball which turns on it. This phenomenon has been studied

by geodesists and astronomers under the name of the fluctuation of latitude.

How have they been enabled to recognise such a minute change? The measurements show, in fact, that the displacement of the pole on the Earth's surface is comprised within the limit of a few metres [or yards] around the theoretical place of the pole. The discovery and measurement of this phenomenon perhaps form the most wonderful result of recent astro-geodesy. It would appear that no phenomenon can escape the eye of the really good observer, and this discovery again shows the depth of understanding contained in Pasteur's thought: "The faculty of opportune speculation is the first step along the way of discovery."

The movement of the poles was discovered as follows: Every point of the Earth is marked on maps or on terrestrial globes by two quantities: (1) the longitude, which indicates its distance from a fixed meridian (that of Greenwich is the standard for the whole world); (2) the latitude, which gives the distance from the equator, reckoned along the meridian of the point in question (Fig. 9). Astronomical observations do not give this latter angle directly, but its complement, the colatitude, which is the difference between it and a right

angle. The problem of finding the latitude, therefore, resolves itself into determining the angle made by the Earth's polar axis with the vertical at the place of observation. Latitude determination is the everyday occupation of travellers, sailors, and astronomers; terrestrial explorers use the theodolite, sailors the sextant, and both easily give results accurate to within twenty seconds, that is to say the error of position would not surpass 600 metres in the north-south direction. Astronomers, with the aid of meridian circles, can find the latitude within less than one-tenth of a second, which means that the possible error of the latitude assigned to the place of observation does not exceed three metres!

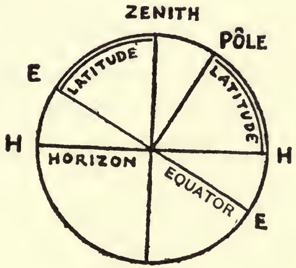


FIG. 9.—Latitude and Co-latitude.

Now, in 1889 and 1890, the observatories of Berlin, Potsdam, and Prague found that their latitudes, frequently measured by the astronomers doing meridian work, varied continuously, and what was even more remarkable, all three latitudes varied in the same sense, as if the North Pole was slightly approaching these towns. The precision

of the instruments employed and the experience and ability of the observers obviated the possibility of these discrepancies being merely fortuitous errors, especially as they were always of the same order of magnitude, viz., several tenths of a second.

In face of these facts, the International Geodetic Association determine to elucidate the matter as completely as possible by making a crucial experiment.

Consider two points A and B of the Earth (Fig. 10) at the same distance from the pole, that is to say on the same parallel, but opposed to one another, their longitudes differing by 180°. If the North Pole moves and thus becomes nearer to one of them, passing from P to P, say, it will recede an equal distance from the other point. Therefore, if the latitude of A increase by a certain angle, that of the point B must decrease by the same angle, and vice versa. In 1891, the International Geodetic Association sent to Honolulu the German astronomer Marcuse and the American astronomer Preston. Honolulu and Berlin occupy in re-

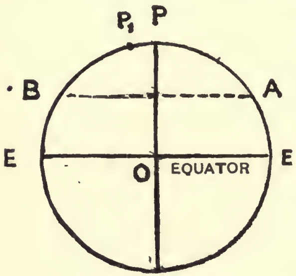



FIG. 10.—Fluctuation of Latitudes.

spect to one another very nearly the positions of the points A and B of the figure. The result was decisive; while the latitude increased at Honolulu, it decreased an equal amount at Berlin. In order to attain absolute certainty, six equidistant stations around the North Pole and two others near the South Pole were established in 1895. It was proved that at each pair of opposite stations, the variations were equal and of opposite sign. The terrestrial poles are therefore not fixed on the Earth's surface but move without cessation.

Having demonstrated qualitatively this curious phenomenon, it remained to observe it quantitatively, that is, to measure it with regard both to the time taken and space traversed.

In the first place, a periodicity has been proved, which, at first sight, seems to have no relation to the periods of the Earth's movements; the pole returns to the same meridian once in every 430 days, that is in about fourteen months. As to the spatial magnitude of the phenomenon, the extent of the motion reaches two- to three-tenths of a second of arc, or expressed as distance, six to ten metres. Figure 11 shows the journeyings of the North Pole over the Earth's surface, between the years 1900 and 1910. It is really remarkable that such an intangible phenomenon has been

discovered and measured. It has only been achieved by the scientific co-operation of all the civilised nations, and such co-operation is becoming

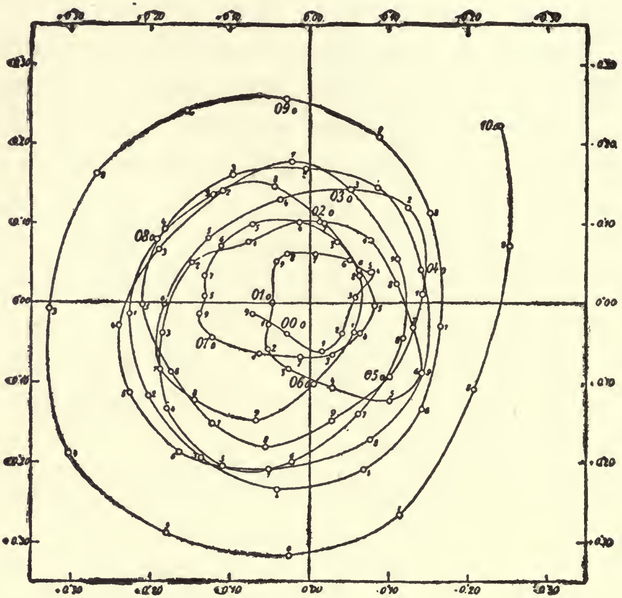



FIG. 11.—Wanderings of the North Pole (each side of the square equals about 65 ft).

more and more the keynote of modern science. Even in science, or perhaps it might be said, especially in science, does union make for strength and strength for action.

The cause of the continuous polar motion is still rather obscure. Chandler in his masterly papers on this subject has attacked the problem

from a purely theoretical point of view, and has given a mathematical analysis of it which has thrown much light upon the subject. By grouping together all the observations made up to the year 1893, he deduced the important result that the movement of the pole could be expressed by a formula containing two terms; the amplitudes of these terms, amplitudes which give the intensity of the phenomenon, vary, in the case of the first term from $\frac{85}{1000}$ to $\frac{185}{1000}$ of a second of arc, which corresponds to a displacement on the Earth's surface of from 2.64 to 5.70 metres, and for the second term from $\frac{115}{1000}$ to $\frac{155}{1000}$ of a second, corresponding to a distance of from 3.56 to 4.30 metres.

The periods of these two terms are on the average, 430 days for the first and 365 days for the second, that is fourteen and twelve months respectively.

It will at once be seen how important this research is. The phenomenon must be produced by the combined effort of two periodical actions, the period of one being fourteen months, that of the other being annual. We have therefore to make a separate study of the two actions.

As regards the former there is an astronomical cause. The periodicity of 430 days can be explained by an astronomical residual, arising from

the action of the Moon on the equatorial bulge of the Earth.

Lord Kelvin and Newcomb have shown that, taken as a whole, the terrestrial globe has an elasticity comparable to that of steel; we shall find an interesting confirmation of this in studying seismic phenomena. Newcomb has shown that if this be so the period of the polar displacement should be 427 days, a figure which agrees remarkably well with the 430 days indicated by Chandler. Furthermore, long-continued observations with tide gauges have demonstrated the fact of the periodical rising and falling of certain shores, for example those of the North Sea near Helder and those of the Pacific Ocean in the neighbourhood of San Francisco. The period of these variations is precisely fourteen months and is therefore equal to that of the first term in Chandler's formula.

The work of Professor Volterra has established that every anomaly presented by the free rotation of a body can be explained by movements which would not change either the body's form, or the intensity of the attraction it exercises on bodies outside it. Now, we know that towards the Earth's centre the excessive pressure to which the fused materials constituting its interior is subjected gives to them a rigidity practically equi-

valent to that of the solid state; on the other hand in the neighbourhood of the crust, where the pressure is greatly reduced, such rigidity does not exist, the fluid state of the material being clearly shown by the lavas from volcanic eruptions. If the entire mass of the terrestrial spheroid be considered to be solid, the phenomenon of latitude fluctuation would be more difficult to explain. Probably there is a circulation of these internal fluid parts. Professor Lagrange of Brussels believes he has found a relation between the periodicity of seismic phenomena and that of polar movement.

Chandler's second term is more easily explained since the period, 365 days, is an annual one. Now meteorological phenomena show a similar periodicity. Consider, for example, the displacement of great atmospheric masses. We have seen that the continents are chiefly grouped in the northern hemisphere; during the winter these continents are much colder than the oceans which surround them and consequently the land is covered with a layer of air of great density. The total mass of air thus collected in winter over the northern continents is in excess of that which in the same season covers the oceans. Professor Spitaler has calculated this excess, and finds it to be fourteen

thousand million tons, that is to day it equals the weight of 1500 cubic kilometres [930 cubic miles] of copper. This enormous mass moves during the summer out over the oceans, and it is quite possible that the annual periodical displacement of such a quantity of air would account for the periodicity of 365 days expressed in Chandler's formula. We must also add that the periodical melting of the polar ice, the seasonal variation of rain precipitation and other phenomena may act in the same way. Dr. Hahn furthermore believes that an annual variation of the Sun's magnetic influence exists. On the whole, therefore, we are in possession of a number of facts, some or all of which may explain the annual periodicity of the polar movement.

In a general way, all the secular phenomena which occur at the Earth's surface act slowly but cumulatively upon the position of the polar axis; thus erosion, rising and sinking of the land surface, the sudden changes produced by seismic phenomena all exert influences which although individually feeble, become considerable by summation. Important and continued geological evolutions, such as those which have marked successive eras in the Earth's history, must have had marked effect on the position of the poles, the more so as,

in primitive ages, the crust was more elastic than it is at the present time. If such displacements were produced in the earlier stages of the Earth's history, many facts known to geologists, the cause of which is still obscure, would be explained by them. And if at some later time the law of polar displacement is fully elucidated, by means of the series of more and more precise observations which scientists will accumulate in years to come, it is probable that much light will be thrown upon the past history of our globe.

Thus, the poles, the conquest of which has stimulated so much noble effort, are points that it is impossible to fix. Each of the explorers fortunate enough to have hoisted the flag of his country at his goal, knew that on the next day, the pole would have escaped its conqueror and would occupy some other nearby part of the surface.

It is thus not possible to lay hold of the pole, to speak figuratively. But if an area 40 metres [130 ft.] square be fenced in about its position on any given day it may be affirmed that the pole will always be somewhere inside this enclosure.

We have studied in some detail the irregularities to which the Earth's rotation and the position of its axis are subject, but these are by no means the only ones. The movement of evolution is also

affected by perturbations, with regard to which a few words will now be said.

In the first place, the eccentricity of the ellipse which the centre of the Earth describes, in accordance with Kepler's Laws, varies; it diminishes uniformly by 64 kilometres [39.5 miles] annually. Decreasing eccentricity implies a nearer approach to a circular form. The speed of revolution round the Sun, which Kepler's Second Law states is not constant, would tend to become more and more so as the ellipse approaches the circle. If the above rate of decrease were to continue, the ellipse would actually become a circle in about 40,000 years, with the result that the Earth's movement would then be quite uniform.[1]

While this change in the elliptical form of the orbit is slowly going on, the ellipse is also displaced in its plane in such a way that the point of perihelion moves from west to east making an entire circuit of the orbit in about 110,000 years, thus introducing a second irregularity into the general movement of revolution. Furthermore, the plane of the orbit, to which that of the terrestrial equator is inclined, does not make a constant angle with

[1] The gravitational pull of the other planets would of course continue their perturbing effect so that the speed of the Earth's revolution could not become really constant.—*Ed.*

the latter. This angle decreases about 48 seconds per century; in other words, the planes of the equator and the ecliptic are approaching one another. But they will never coincide,[1] because the orbital plane oscillates backwards and forwards between two very near limits. The motion nevertheless introduces a third perturbation into the Earth's movement around the Sun. Again, we have to remember that the Earth does not revolve alone around the Sun. It is accompanied by a small companion or satellite, the Moon, whose mass is $\frac{1}{81}$ that of the Earth and whose distance from us is equal to sixty times the Earth's radius. Strictly speaking it is not the Earth, but the complex Earth–Moon system, which revolves around the Sun. Now the duality of the system necessitates that, if the Moon describes a certain ellipse around the Earth, the Earth, whose mass is eighty times greater, describes an ellipse eighty times smaller. The result is exactly as if, having attached two balls to the extremities of a string, one being eighty times heavier than the other, the system was thrown forth into the air so that the string remained stretched; the two

[1] Some modern astronomers believe that they will; that eventually *all* the planets will revolve with their axes perpendicular to their orbital planes.—*Ed.*

balls would thus be obliged to take a *common* movement of revolution and, at the same time, they each would revolve about a point situated on the line joining the centres of the balls, $\frac{1}{80}$ of the distance from the centre of the large ball to that of the smaller.

In the particular case we are dealing with, that of the Moon and the Earth, the force of attraction reciprocally exerted between the two masses, in accordance with Newton's Law, takes the place of the material connection. Consequently, it is the centre of gravity of the Earth–Moon system which describes the elliptical orbit round the Sun. As the masses and distance apart of the two bodies are known, it may be shown that the centre of gravity lies on the line joining the centres of the Earth and Moon, about 1000 kilometres [620 miles] below the surface of the former. It is, thus, a point in the interior of the terrestrial globe, and, as it is markedly eccentric, it produces another anomaly in the Earth's movement around the Sun.

Finally, there is yet another movement superimposed upon all the others; it is a general movement affecting the whole Solar System which is traversing intersidereal space, moving in the general direction of the star Vega with a consider-

able velocity, viz., more than 20 kilometres [12 miles] per second. By reason of this general movement of translation, the Earth's elliptical orbit is actually an immense elliptical spiral, like a screw-thread whose diameter is the major axis of the terrestrial orbit, that is to say, more than 297 million kilometres [185,450,000 miles]. The step of the thread, the distance the Sun and whole Solar System move in the course of a year, is more than 627 million kilometres [388,750,000 miles]. The point of the sky towards which this journey appears to be directed is called the apex.

The fact of this movement, and its measurement, have been achieved by a very beautiful application of the theory of the propagation of vibratory movement, an application which Doppler and Fizeau worked out in principle and which modern astrophysicists such as Deslandres and Hale have put into practice with notable results. When a luminous source is in motion in the direction along which we see it, that is to say when it comes either directly towards us, or moves directly away from us, in a straight line, the velocity of the light reaching us from the source is affected by the actual velocity with which the source is moving. Consequently, if the light coming from this moving source be received in a spectroscope, the rays

of the spectrum will be displaced either towards the violet end or the red end, according to whether the source is approaching us or receding from us. Precisely the same thing occurs if the eye of the observer is in motion relative to a fixed source, or, again, if the two are relatively displaced in any way. In all cases a displacement towards the violet indicates that the distance between the eye and the source is diminishing; one towards the red indicates the reverse, viz., that the distance is increasing.

The theoretical explanation is the same as that which obtains with regard to the phenomenon observed in the case of a whistling locomotive; the pitch of the note varies according as the locomotive is coming towards or receding from us.

The Earth, as a whole, has therefore twelve different movements which science has been able to analyse, and of which the effects have been studied and the causes discovered. We shall see later that, not in its entirety but as regards its crust alone, the Earth is subject to other movements of astronomical origin; these are the oceanic tides, and the terrestrial tides, which give to the ground a perpetual movement of exceedingly great complexity, its apparent stability being only an illusion.

# CHAPTER V

## GRAVITY

CERTAINLY one of the mechanical phenomena, one of the manifestations of movement, which most strikes the least experienced observer is the fall of bodies. When a material body, which has been raised to a certain height, is deprived of its support, it falls to the ground, following the line which joins the original position of the body to the centre of the Earth, at least as nearly as our senses and instruments can show.

This line is called the vertical of the place. All bodies obey this law of falling, which is the law of gravity. Consequently, liquids by reason of their fluidity dispose themselves so that their free surfaces are at each point normal to the vertical at the point in question. Such surfaces are therefore curvilinear, and their formation is due to the combined action of the laws of gravity and centrifugal force which give to the Earth its ellipsoidal form. The surface of the oceans imaginarily

prolonged under the continents is, as we have seen, called the geoid. If it be of very small extent, the curvilinear surface of a liquid mass coincides with its tangent plane and in this case only does it form a horizontal plane perpendicular to the vertical of the place.

Gravity thus furnishes us with the data as to our fundamental directions of horizontality and verticality. If we suspend a heavy body on a string attached to a fixed point, the string, being flexible, takes the direction along which the body is drawn towards the Earth. It forms a plumb line which indicates the vertical of the place.

The weight of a body, which makes it fall towards the Earth, is a particular case of the universal attraction between portions of matter; it is not a distinct kind of force. The attractive force between two bodies is proportional to the product of masses and in inverse ratio to the square of their distances. In the case we are considering, the Earth is one of the bodies, viz., that with the preponderating mass. Since it is nearly spherical, its effect, on anything outside it, is the same as if its entire mass was accumulated at its geometrical centre. The other body, that which is attracted, is the one which falls to the ground. We have thus, under our very eyes, an illustration of the

law which Newton enunciated, and which governs the movements of the bodies in infinite space.

Father Ximénès, as early as 1757, had pointed out that the balance could demonstrate the identity of weight and gravitation, but lack of precision of the instruments of his period prevented him from realising his idea. The experiment devised by the Spanish scientist was carried out by Jolly towards the end of the nineteenth century. The essentials are as follow: A balance is placed on an elevated support, such as, for example, the flooring of a higher storey of a house, and a long fine metallic wire is suspended from below one of its scale-pans. On the latter, say the right pan, a weight of one kilogram [2 lb. 3 oz. 4 dr.] is placed, while on the other, the left pan, a similar weight is put to give equilibrium. If the weight be now hung on the end of the wire, after removal from the pan where it formerly was, the other weight being untouched, the equilibrium is destroyed because the first weight is now nearer to the centre of the Earth, and so is attracted with greater force.

It is easy to calculate the difference; for a height of 300 metres [990 ft.], such as that of the Eiffel Tower, the variation is $\frac{1}{10,000}$ of the weight. In other words if the above experiment were

made from the height of the Tower with the weight of one kilogram suspended at the end of the wire near the ground, it would be necessary to add one decigram [1.54 gr.] to the other pan to restore equilibrium. For a height of 30 metres [99 ft.], one centigram [.154 gr.] would be required, and for one of 3 metres [9.9 ft.] the difference would be one milligram [.015 gr.] Now, the sensitive balances to be found in modern physical laboratories will easily weigh a kilogram to within $\frac{1}{12}$ of a milligram. The experiment may thus be easily carried out between the ceiling and floor of a room; it is extremely instructive, and should be done in schools and colleges at the beginning of every course of physics.

Once it is realised that weight is identical with universal gravitation, it will be seen that it is not strictly correct to say, as is done in courses of elementary physics, that "gravity is a force constant in magnitude and direction." It is not constant in magnitude, for it varies with the least vertical displacement, and we shall see that it also varies with the least horizontal displacement; neither is it constant in direction, since it is directed along the vertical, and two neighbouring verticals meet about the centre of the Earth. And, if within the limits even of a room it is possible to

demonstrate a variation in its intensity, it would be equally possible to prove astronomically, by means of the meridian circle and variation in the direction of the vertical with respect to the celestial sphere, in the same space.

The laws of the fall of bodies given in similar courses of physics are similarly not exact. The law of velocities and the law of distances are verified with an apparatus called Atwood's machine, generally 2 metres [6.5 ft.] in height. Now, Jolly's experiment succeeds with a difference of height of two metres; it indicates a difference of two-thirds of a milligram [.010 gr.] for the weight of one kilogram [2 lb. 3 oz. 4 dr.] transferred from the top of the apparatus to the bottom. Therefore, if the experiment with Atwood's machine appears to succeed, it is thanks to the systematic lack of precision of the apparatus, to the unconscious assistance of the experimenter, and the inexperience of his pupils.

On the other hand, we may demonstrate for purposes of instruction the existence of gravitation by that of weight; if the story be true, Newton in watching the fall of an apple had the first inspiration of his discovery of the law which governs the movements of the celestial bodies in space.

The variation of the force and the direction of

gravity demands methods and instruments of exceptional precision for its measurement.

The determination of the direction of gravity resolves itself into the determination of the true vertical at each point on the Earth's surface. This vertical is normal to the ideal surface which is called the geoid, formed, as before stated, by the prolongation of the oceanic surface underneath the emergent land masses. The determination of the direction of gravity therefore necessitates the study of the exact form of the geoid, that is to say, the form of the Earth itself. A special science, geodesy, deals with this matter and we shall shortly have to return to its methods more fully.

The measurement of the intensity of gravity at a given place is a problem in mechanics. Since gravity is a force, we may study that force by the effects which it produces; there are two distinct ways of doing this, the dynamic method and the static method. The first consists in studying the movement impressed on a given system by the action of the force in question; in the second we maintain a state of equilibrium of the body, which is submitted to the action of the force which we require to measure by counterbalancing it with another force, the value of which is known.

The dynamic method has been, up to the pre-

sent, the one almost wholly employed, and the only form which this method takes is that of oscillations. When a body capable of oscillation, such as a magnetised needle, for example, be displaced from its position of equilibrium, it tends to revert to it, and executes a series of oscillations, the amplitude of which decreases logarithmically. If we place the pole of an electromagnet near this needle, the latter will execute a certain succession of oscillations, which can be determined by observation. Now, if the intensity of the current which circulates around the iron nucleus of the electromagnet be increased and the intensity of the magnetic force due to it consequently also augmented, the needle will, under the influence of the greater force, oscillate more and more quickly in proportion as the force increases.

This is exactly analogous to the method used in studying gravity. A heavy body is taken, suspended at the extremity of a fine, but inextensible, thread. This constitutes a plumb line. The body is displaced from its equilibrium position and left to itself; under the action of gravity, which tends to bring it to a position as near as possible to the Earth's centre, it executes a series of oscillations of gradually decreasing amplitude, thus constituting a pendulum. Should the inten-

sity of gravity increase, the oscillations will be more rapid and, on the other hand, in a place where the intensity is feebler, they will be slower.

This apparatus would be what mathematicians call a simple pendulum. If the thread were free from friction at its point of suspension, if it were without mass, while still remaining rigid and inextensible, and if the suspended body had no dimensions but were merely a heavy material point, the law governing its movement would be also simple; the oscillations, while subjected to a logarithmic decrement, would continue indefinitely. When they became of extremely small amplitude, they would be isochronous, and their period would be proportional to the square root of the length of the thread, and inversely proportional to the square root of the intensity of gravity at the place where the pendulum is.

Unfortunately, this ideal pendulum is absolutely unrealisable in practice; however fine the thread may be, it has some mass; the body which is suspended on it, and which is usually in the form of a ball, has dimensions and so cannot be considered as a mathematical point however great its density may be. Furthermore, whether the thread be suspended from a knife-edge or held in a vice, friction is bound to come into play; also the whole

oscillates in a resisting medium. For these reasons the experiment so beautifully simple in principle is extremely difficult to carry out actually.

Nevertheless, Bouguer and La Condamine attempted to measure the intensity of gravity with a pendulum approaching as nearly as possible to the simple pendulum, but it is Borda to whom the credit is due of making the first really precise experiment, from which the law of the oscillations and the value of gravity at a given place could be deduced. The famous sailor tried to realise as far as possible the conditions of the simple pendulum. For the heavy body he used a platinum ball, the high density of which enabled it to be of relatively small size; the suspending wire was also of platinum and hung from the knife-edge of a balance. The wire carried at its lower end a hollow greased metallic cap to which the ball of platinum was fixed by simple adherence. The whole was therefore composed of two parts: the ball, and the knife-edge wire-cap system. Borda measured the duration of oscillation of the complete pendulum; then, removing the ball, he displaced, by means of a screw with a heavy head, the centre of gravity of the knife and increased this displacement until the knife-edge wire-cap system, oscillating as a pendulum, had the same

period of oscillation as the original pendulum furnished with the ball. In these circumstances, the suspension system did not enter into the calculation at all, and the result was as if Borda was using a pendulum constituted of a wire without mass supporting a heavy sphere. Now the formulæ of mechanics enable one to calculate the moment of inertia of a sphere with respect to an exterior axis around which it oscillates; the problem was thus solved, save for the corrections due to the perturbing action of air-currents. Borda had previously devised a formula which allowed for the amplitude of the oscillations when these were not extremely small.

This method has been abandoned, though it is difficult to assign a reason for this; it only requires the measurement of the duration of oscillation, a measurement which is equally necessary in all cases, whatever form of pendulum method be employed, and also the measurement of the distance between the knife-edge and the centre of the ball. It allows of moving the heavy ball with reference to the cap in which it fits, by twisting it round, and so eliminating any error due to the non-homogeneity of the ball, the mean of experiments with different positions being taken. The whole experiment may be carried out in vacuo,

and, consequently, it follows that it is susceptible of the maximum degree of precision that we can attain at the present time.

In spite of this fact, modern geodesists have given up the simple pendulum method and only use that of the compound pendulum.

The compound pendulum consists merely of any body whatsoever, which is caused to oscillate about any axis not passing through its centre of gravity. Under the action of gravity the body originally takes up a position of equilibrium, and, when it is displaced from this position, it executes a series of oscillations according to the pendulum law. But, even if the oscillating body had some definite geometrical form, the experiment would hardly be suitable for the precise determination of the intensity of gravity if De Prony, the inventor of the dynamometer which bears his name, had not discovered a curious and unexpected property characterising the compound pendulum.

Let us take a body of any form whatever. Near one of its extremities we fix a transverse axis and make the body oscillate about this axis, which is called the axis of suspension. These oscillations would have a definite period which is measured and noted with care. We next make use of a second axis parallel to the first one and placed in

such a way that if the body be caused to oscillate round this new axis, to which the name axis of oscillation is given, the new period of oscillation is exactly the same as the former one. The science of mechanics shows that it is always possible to find the point where this second axis must be placed, in any body; there are actually several such places. The two axes, those of suspension and oscillation, are reciprocal to one another.

This being done, it may be proved that when the axes have been adjusted as above described, the distance between them is equal to the length of the simple pendulum that would have the same period of oscillation. This is the salient feature of Prony's discovery.

The importance of this will now be seen. The simple pendulum, unrealisable as such, is indirectly realised by means of the compound pendulum. All that is necessary is to find by repeated experimental trials the position of the two axes, to measure the distance between them with all possible precision, and to determine the period and amplitude of the oscillations of the body. The value of the intensity of gravity at the place where the experiment is made may be deduced from the formula for the simple pendulum.

Although the principle of this method is not

complicated, its practice is a very delicate matter on account of the precision which is necessary, and which exceeds $\frac{1}{300,000}$ part.

In the first place, it is necessary to correct the pendulum for the variations in length due to changes in the temperature of its surroundings. Then there is the influence of the nature of the medium in which the body oscillates, that is to say, the disturbing effects of the air.

One effect which the air has on the pendulum is to exert a thrust upon it, lessening its apparent weight, according to the principle of Archimedes, with the result that the pendulum oscillates a little more easily under the action of a given force than if the same experiment were conducted in vacuo. Again, it offers resistance to the movement of the apparatus, a resistance which affects all moving bodies. This is easily recognised by artillerymen and by cyclists, and it is on account of such resistance that birds and aeroplanes can move through the atmosphere. The degree of resistance increases very rapidly in proportion as the velocity of the body in question is augmented. In the particular case of the pendulum, which oscillates slowly, it is very feeble, but nevertheless not negligible when the degree of precision we require is taken into account. Furthermore,

there is a third effect; the air is to a certain extent carried along with the moving pendulum, and from this it follows that the loss of weight due to the atmospheric thrust above mentioned is doubled. Finally, as the air is far from being a perfect fluid, it possesses a certain viscosity and this viscosity helps to retard the oscillatory movement of the pendulum.

These complex, and by no means negligible, effects of the air may be eliminated by making the pendulum oscillate in a vacuum, a procedure which has only recently been carried out in practice.

The determination of the length of the pendulum, that is to say the distance separating the two parallel axes, is a delicate operation. These axes are represented by two knife-edges, the edges being turned towards one another. It is possible to obtain the value of this distance to within a micron.[1]

The measurement of the duration of the oscillations is an even more delicate matter; it necessitates the determination of a period of about one second with a precision of the same order of magnitude as that which we wish to attain in the resulting value of gravity.

An idea which readily occurs to one is to measure

[1] A micron ($\mu$) $= \frac{1}{1000}$ of a millimetre $= .00003937$ in.

by means of an astronomical clock, regulated to keep sidereal time, the duration of say 1000 oscillations and to divide this quantity by 1000. This is the method of passages; it is long and tedious and tends to tire the observer and cause him to make large errors. It would be possible to re-introduce this method at the present time, registering the oscillations by photography on cinematograph films and perhaps a very good result could be thus obtained.

The other artifices are preferred: the method of coincidences devised by Mairan, and the method of phases applied by the Austrian general, von Sterneck. The latter is the one now most employed.

The pendulum may be used to give information of two different kinds, either to furnish the absolute value of the intensity of gravitation at a given place, or to give the relative value of the intensities at different stations on the Earth's surface.

The absolute measurement is difficult as we have already seen, since it implies the determination of a length and an interval of time with the greatest precision. The relative measurement is easier and thanks to the method instituted by General von Sterneck it is now in current use.

It consists in taking a pendulum, which of course remains of invariable dimensions, and causing it to oscillate successively at two distinct stations, in identical conditions, measuring in each case the duration of the oscillation. The formula for the simple pendulum shows that the intensities of gravity at the two stations are in the inverse ratio of the squares of the oscillation periods.

This being so, it suffices, in order to determine the absolute value of gravity at various places on the Earth's surface, to measure it absolutely at any one place, Paris for example; then the same pendulum is taken to the required places and the values relative to that at Paris obtained. In this way a map showing the values at different places may be made.

Although the method used for this practical application of the pendulum to the determination of gravity is a very good one, nevertheless it requires a series of complex operations and long and delicate manipulations. Also, the measurements are difficult, and the apparatus fragile and bulky. An astronomical clock is, in fact, necessary, as is, also, an instrument to observe the stars and so regulate the clock to keep sidereal time. Then there is the pendulum, or rather

pendulums (von Sterneck used four), a firm support to hold them and an air-pump and receiver to create a vacuum in which to place them. Finally, an apparatus is necessary to measure the coincidences, and the whole constitutes, as will be seen, a complicated arrangement, exacting as regards the personnel and necessitating an expenditure of much time.

Physicists have therefore endeavoured to find if it would not be possible to measure the intensity of gravity directly by a static method, attaining equilibrium between gravity which tends to draw a heavy body to the ground and an opposing force, which is known or measurable, equal and of contrary sign. The principle of such an arrangement is attractive because if it could be realised with the necessary precision, the intensity of gravity at a place could be deduced by a simple reading of the graduation.

The most simple kind of such an apparatus is the spring balance. The elasticity of stretching of a spiral spring depends only on the nature of the metal and not on the value of gravity. If, therefore, a very sensitive balance be made use of and taken to different places, the same body being always suspended from it, the body will appear to weigh more or less according as the

intensity of gravity at the place in question is stronger or weaker. Consequently the spring is stretched to various extents in the different parts of the globe to which it is taken and the variations in length give us the relative values of gravity in these places.

But it is a far cry from theory to practice and the good spring gravity measuring machine has yet to be constructed. However, Threlfall has made an instrument which has a high degree of sensitiveness; he does not employ the property of stretching but that of the torsion of a very fine thread of quartz, and geo-physicists anticipate that they will be able to do good work with it.

An elasticity to which scientists have for a long time given their attention is that of a gas forced to occupy a constant volume by the pressure of a column of mercury. The mercury, the weight of which is responsible for the pressure to which the gas is submitted, weighs more or less according to the value of the intensity of gravity at the place of the experiment. The result is, therefore, that we balance a pressure, which always remains the same, with mercury columns of different densities of which the heights will thus be in inverse ratio to the densities, that is to say to the corresponding intensities of gravity. The

method is simple and ingenious but unfortunately the great sensitiveness of the pressure of the gas to variations of temperature ($\frac{1}{273}$ part per degree Centigrade) renders the method very difficult in actual practice.

Count Wüllersdorff-Urbair, of Vienna, has attempted to avoid this difficulty by only making use of a gaseous mass as an intermediary between two manometric arrangements, one of which depends on gravity while the other, serving as a standard, does not vary with anything. The mass of gas chosen for this purpose is that of the atmosphere itself. Let us imagine that the pressure of the atmosphere is measured simultaneously by means of two barometers, one a mercury barometer and the other a spring barometer, such as an aneroid. At the first station, the two instruments are made to agree, but this agreement will not hold good at a second station, for which gravity has a different value. In fact, the mercury weighs more in the place where the force of gravity is stronger. It is then denser, and in this denser condition a column of mercury of less height will balance a pressure which would have necessitated a longer column of mercury of normal density. The aneroid barometer should always indicate, on the contrary, the true pressure. The greater

or less extent of disagreement between the two instruments enables the variations of gravity to be deduced, the atmospheric pressure acting only as an intermediary agent.

The method appears good but it is vitiated by a weak point, viz., the aneroid barometer. Depending upon the elasticity of a spring it is subject to vicissitudes; the elasticity of steel changes greatly with temperature and also slowly varies with time. The method, therefore, would not have been susceptible of the necessary precision if the Swiss physicist Guillaume had not conceived the idea of replacing the aneroid barometer by an instrument called the hypsometer, which gives the value of the atmospheric pressure by determining the value of the boiling point of water, which depends on that pressure. The tables of boiling points and the respective atmospheric pressures they correspond to are drawn up for the normal values of the pressures, measured by a column of mercury at zero Centigrade, at sea level, in a definite latitude on the Earth's surface, viz., that of 45°. So that if the indications of the barometer and hypsometer do not agree, the difference gives the variation of gravity. The hypsometer has been brought to a high state of perfection, due to the progress of thermometry. Professor

Mohn of Christiania has made use of the method with great success on land, and the German geodesist, Dr. Hecker, has attempted to utilise it in the course of two voyages, one in the Pacific and one in the Atlantic, in order to obtain the value of gravity on the open sea, where the employment of a pendulum is quite impossible. The maximum degree of precision which may be obtained by this method appears to be one part in 50,000, and this is amply sufficient to detect certain anomalies in the normal value of gravity.

In a general way all physical phenomena, in the analytical formula for which occurs the value of the intensity of gravitation, the symbol for which is $g$ may be utilised to determine this quantity. Thus, the fall of bodies, the velocity of sound, and the pitch of the musical note emitted by a vibrating wire stretched by means of a weight on a sounding box will give data from which the value of $g$ may be deduced. The value of $g$ also enters into many phenomena in connection with wave systems. The velocity of propagation of a seismic wave of translation over the surface of a large ocean is a function of the depth of the ocean and the mean value of the intensity of gravitation at its surface. Furthermore, all ex-

periments which have to do with a pressure may be made to give the required value of *g*.

Nevertheless, the pendulum method remains by far the most precise; the value of *g* which it will give in the hands of a good experimenter may attain a precision of one part in 300,000. It is true that many geodesists give values for *g* as if they were precise to the extent of one part, or even less, in 1,000,000. But this precision is only apparent and has its origin in the figures resulting from the application of the method known as that of least squares, made use of in the discussion of experimental errors. This method, though excellent in certain cases, often masks errors of experiment. If we have twelve numbers each of seven figures, which express twelve different measurements of some one quantity, and if the first five figures are common to all the twelve values, we may affirm that the experimental precision of the measure is expressed by the decimal order of the last of these figures; in the case cited, this will be a precision of the order of one part in 100,000. If the results be discussed by means of the mathematical theory of probabilities, in particular by the method of least squares, a probable error will be found less than a certain number in taking a value which the calculation determines. But

this is a theoretical precision and not an experimental one. If the twelve numbers above taken as an example express, let us say, twelve determinations of the coefficient of expansion, a physicist who will have to use the value of this coefficient in subsequent work should only take the first five figures as exact ones; they are the only ones which he can be quite sure about, since they are common to all the twelve determinations. The use of one of the subsequent figures may lead to a greater or less degree of probability, but not to certainty.

We shall now briefly consider the results that the methods above summarised have given, with reference to the point of view of the variation of the intensity of gravitation over the surface of the globe.

First of all, what is the absolute value of gravity? This quantity has been determined by General Wefforges at the laboratory of weights and measures at Sèvres, in 1890–2, and at Vienna by General von Sterneck. The absolute value of gravity at Paris is 980.97 centimetres [386.208 in.] and at Vienna 979.98 centimetres [385.818 in.]. Some explanation must be given as to why the values should be expressed in centimetres. The reason is the application of a law relating to uniformly accelerated movement. It may be shown by

mechanics, that when a constant force acts on a body originally at rest, it communicates a movement of uniform acceleration to the body, or in other words a movement the velocity of which increases, during each unit of time, by the same constant quantity, which is called the acceleration. Acceleration is therefore a length, and is naturally expressed in centimetres. The contradiction between the expression of gravity by a length and what has been shown above as to its variability will be noted. The expression of the intensity of a force by the degree of acceleration which it imparts to a material mass implies that the force in question remains constant. Now gravity is only a constant force on condition that the body on which it acts remains absolutely immobile; if it move, either up or down or parallel to the surface of the globe, the value of gravity changes. In order to obtain an acceleration to measure the force producing it, the body must fall and hence there will be a variation in the value of the force acting on it.

To avoid this difficulty we conventionally define the acceleration of gravity, and imagine that gravity, which has a fixed value when it acts on a body placed at a certain point, will maintain the same value during the fall of the body on which it

acts. Then, and then only, will the movement of fall be uniformly accelerated and such uniform acceleration may serve as the measure of the intensity of gravity at the initial position of the body. It will be seen that these imaginary conditions are not practically realisable.

With this understanding, viz., the imaginary hypothesis as to the constancy of gravity throughout the extent of fall of the body, we shall now consider how these ideas may be applied to the measurement of the intensity of gravity by means of the pendulum.

A pendulum is a falling body; at its position of equilibrium it merely represents a plumb line, but when pulled aside from this position it tends to return to it, since it is acted on by gravity and caused to fall down again towards its original position, which is that nearest the Earth's centre. The height of the fall is thus the distance mM (Fig. 12). This distance defines the degree of precision of pendulum measures. For a fall of 300 metres [990 ft.], the variation in the value of gravity is about $\frac{1}{10,000}$ part of its origi-

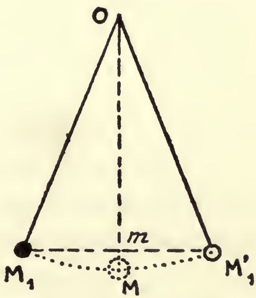



FIG. 12.—Precision of Pendulum Measures.

nal value. For a fall of 30 metres [99 ft.] it will be $\frac{1}{100,000}$ part; for one of 3 metres [9.9 ft.], $\frac{1}{1,000,000}$ part, and for a fall of 3 centimetres [1.17 in.] it will be one hundred millionth, while for one of three-tenths of a millimetre [.012 in.] it will be one ten thousand millionth part. Now for an angle $\alpha$ of oscillation equal to a degree, the height mM is equal to three-twentieths of a millimetre [.005 in.]. Consequently, the corresponding variation in the intensity of gravity is about one twenty thousand millionth part of its value, and this fraction therefore expresses the limiting precision of pendulum measurements. If it be required in the future to attain a greater precision, it will be necessary to take account of this little variation in gravity during the distance mM and to devise a new mathematical analysis dealing with the phenomena in these conditions.

But the experimental precision of pendulum measures does not actually exceed the $\frac{1}{500,000}$ part and perhaps does not attain even this, so that in practice, in the operation of measuring the acceleration of gravity by the aid of pendulum observations, we may neglect the almost imperceptible variation in the force along the path of the fall, the resulting error being far smaller than the errors of experiment. Consequently the

actual methods used for the determination of *g* are legitimate and accurate.

There is a force which partially opposes that of gravity, namely, the centrifugal force due to the Earth's rotation and we have to compound the two forces to find the resultant effect. A point A

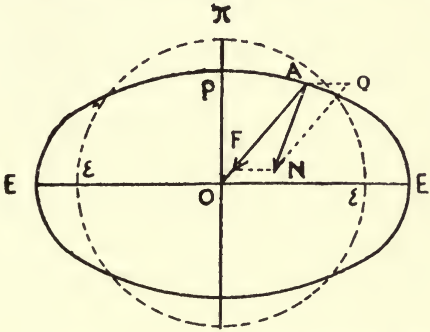



FIG. 13.—Form of the Earth determined by the combined actions of Gravity and Centrifugal Force.

(Fig. 13) on the surface of the Earth (supposed spherical) is attracted towards the centre by a force AF but at the same time the Earth's rotation tends to drive it in the direction AQ, perpendicular to the polar axis. The point A is consequently subjected to two forces, the attraction AF and the centrifugal force AQ; this last increases in proportion as the point lies nearer the equator and diminishes with decreasing distance from the pole. The resultant of these two forces, that is

to say the real force to which the point A is subjected, is thus a force AN which is not directed toward the centre of the sphere. Since the Earth was originally fluid it attained an equilibrium surface such that it was perpendicular at every point to the resultant force at that point. It may be shown mathematically that such a surface would be an ellipsoid of revolution rotating about its minor axis and this is why the Earth is not spherical but has an ellipsoidal figure. As a result, the pole P is nearer to the centre O than a point E on the equator, the former distance being less and the latter one greater than it would be if the Earth were spherical. In this case the equator would occupy the position ee. It follows that the Earth bulges at the equator, having the added portion Ee formerly mentioned.

It may be calculated that at the equator the centrifugal force is $\frac{2}{286}$ part of that of gravity, and 289 being the square of 17 we have noted the consequences that would result if the Earth turned seventeen times quicker. Gravity would then be, at the equator, exactly balanced by the centrifugal force, and no body would have any apparent weight. As it is, this force is sufficient to cause the variation of gravity to the extent of $\frac{1}{289}$ part between the equator and the pole.

Another cause also produces a variation of gravity between the equator and the poles. Because of the Earth's ellipticity, points on the equator, farther from the centre, are attracted less than points close to the poles which are nearer the centre. This second cause of a continuous variation of gravity with position on the Earth's surface acts in the same way as the first, viz., a decrease of gravity towards the equator. There is also a third cause, which on the contrary, acts in the opposite way from the first two, viz., the influence of the equatorial protuberance. This mass, Ee in section, exercises an additional attraction beyond what would occur in the case of a perfect sphere, and so increases the force of gravity at the equator.

Geodesists have found a simple formula to express the resultant variation of gravity between the Earth's poles and equator, which allows for all three causes. If we know the value $g_0$ of gravity at the equator, its value in a place whose latitude is $\lambda$ is given by adding to $g_0$ a fraction of $g_0$ obtained by multiplying it by the $\frac{1}{193}$ part of the square of the sine of the latitude.[1] Since $\frac{1}{193}$ is nearly $\frac{1}{200}$, we can state that in round numbers a body moved from the equator to the

[1] $g_\lambda = g_0\left(1 + \frac{1}{193}\sin^2\lambda\right)$.

pole apparently gains in weight $\frac{1}{200}$ part of its original weight. If the body weighs a kilogram [2 lb. 3 oz. 4 dr.] at the equator, on a dynamometer (not on a balance), it will weigh 5 grams [77 gr.] more at the pole.

The value $g_0$ of gravity at the equator is expressed by 978.07 centimetres [385.057 in.].

Pendulum observations can therefore serve for the determination of the flattening of the Earth. Clairaut was the first to give a complete analysis of this matter and it was again undertaken by the eminent German geodesist Helmert, who in 1901 found the value $\frac{1}{298}$ from a discussion of all the determinations of gravity. Geodetic measurements by direct measures of meridian arcs gave Bessel the result $\frac{1}{299}$, and astronomical calculations based on precession, nutation, and inequalities in the Moon's movements have led to the value $\frac{1}{297}$ deduced by the mathematicians Radau, Poincaré, and Hill. The agreement between the three figures obtained by such different methods is truly wonderful.

To the continuous regular variations of gravity must be added that caused by the elevation of the point of observation above the geoid, the cause of which is illustrated by the experiment of Jolly, previously described; its calculation is easy. But

there are also accidental variations of gravity, anomalies, which we shall now deal with.

We have seen, in the course of the preceding pages, that the measurements of the intensity of gravity enable a precise value of the flattening of the terrestrial globe to be obtained. We have seen that the laws of the central attraction and centrifugal force combined would impose on the originally fluid Earth the shape of an ellipsoid of revolution, turning about its minor axis, which produces the flattening experimentally found.

The problem of finding the exact form of the Earth is one of a very great complexity. If it were required to determine point by point a figure similar to that of the Earth with its contour projections and representation of the various altitudes, the problem would surpass human power. Fortunately several simplifications are possible. In order to resolve the question, sufficiently, the thing to do is to consider three surfaces, each defined in a different way. These surfaces are as follows: First, the geographical surface, that is to say, the exterior surface of the terrestrial globe, comprising the surface of the continents and the free surface of the seas and on which rests the atmosphere that envelops us; secondly, the geoid, of which we have already spoken, and which is the

oceanic surface supposed to be prolonged below the continents; thirdly, the geodetic surface, which is defined geometrically and which will be a surface of reference for the purpose of our study; it is an ellipsoid of revolution calculated to agree exactly with the most precise and extended measurements of meridian arcs.

The geographical or real surface is that on which we live and on which consequently all our observations and experiments are made, including the astronomical determination of fixed reference points in the celestial sphere. On this surface of the crust we have measured arcs of the meridian which have enabled us to determine the dimensions of the ellipsoid of reference. But what we wish to know is the exact form of the second surface above mentioned, viz., the geoid, the liquid surface which by its fluidity obeys the combined laws of attraction and centrifugal force. Moreover we know that, on account of the relatively very slight mean continental altitude, as compared with the Earth's dimensions, the real surface does not differ much from the surface of the geoid.

We are, thus, lead to study a surface, the geoid, that is intimately related to the real surface, and which does not differ greatly from the surface of reference, that is to say, the theoretical ellipsoid.

If gravity were always the resultant of the centrifugal force and of the attractive force, the geoid would theoretically coincide with the theoretical ellipsoid. But gravity, the direction of which is found at every point by that of a plumb line, that is to say by the true vertical, is not simply this resultant at every point; it is subject to anomalies arising from the local irregularities of the crust, such as high continental plateaux, mountains, beds of minerals of different densities from the surrounding rocks, the discontinuities between land and sea, etc., which introduce local attractions acting on and deviating the heavy mass suspended at the end of the plumb line, thus deflecting the vertical.

And, as the geoid is normal to the direction of the vertical at each point of its surface, it follows that every anomaly of gravity, every local deviation of the vertical, introduces a deformation into the surface of the actual geoid.

It is, however, to be noted that an analysis of the matter will afford us much useful information with which to begin our study.

In the first place, it may be shown that it is always possible to place a given ellipsoid of revolution, chosen as surface of reference, in such a way that its surface shall contain a given point of the

geoid and that at this point the astronomical longitude, latitude, and azimuth shall be respectively equal to the geodetic longitude, latitude, and azimuth defined by means of the surface of reference. Also, when this is done the axis of revolution of the ellipsoid is parallel to the polar axis of the Earth. Then in every point where the real vertical of a place on the geographical surface intersects the ellipsoid of reference, we may obtain the astronomical elements, above mentioned, by observation and the geodetic elements by calculation.

We have said that the local attractions modify, in places, the actual surface of the geoid, and in such places the geoid does not coincide with the surface of reference. Consequently as the latter is known by definition, in order to find the true surface of the actual geoid, it is necessary to know the vertical distance separating the points where the normal to the ellipsoid meets, in the first place, the ellipsoid, and in the second place, the geoid; this is astronomical levelling. It is thus necessary to have the largest possible number of observations of precise astronomical observations made on the real geographical surface.

The lack of homogeneity in the constitution of the terrestrial crust, and the separation of lands

and seas with the consequent discontinuity of density, are the chief causes of local anomalies and hence of the corresponding deviations of the direction of the vertical. The pendulum, with its precision of about 1 part in 500,000, may be used to discover local gravitational anomalies. If gravity at a place is not affected by such causes it has the value which the formula previously given assigns, depending on the square of the sine of the latitude. If the pendulum observation gives a different value, there is an anomaly, positive or negative according as the observed value of gravity is greater or less than the calculated value. The numerical value of the difference between observation and calculation gives the anomaly, qualitatively and quantitatively after the value measured has been reduced to sea-level by correction, and after the altitude of the place of observation, which implies a diminution of the attractive force that is easily worked out, has been allowed for.

The anomalies of gravity are of two kinds: sometimes they are purely local and due to the attraction of neighbouring masses, whether the higher parts of the relief, such as mountains or whether underneath the ground in the form of mineral deposits of abnormal density. Sometimes

also they have a systematic character and follow a veritable law with regard to their variations.

Local anomalies have a very great significance for geologists; they give valuable indications as to the density and position of mineral masses which it is impossible to see or sometimes even to reach at all. An earnest and profound study of the anomalies has led German geodesists and geologists to discover a long subterranean mass, directed from west to east, passing under the Elbe and the Oder. Swiss geodesists, from anomalies observed in their country have arrived at some very remarkable conclusions as to the constitution of the subsoil, in particular in the region of the Engadine.

Heim of Zurich has emphasised the importance of these studies, in relation to the conditions of formation of the terrestrial crust. The earth is constituted by a lithosphere (mineral crust) and a barysphere (internal nucleus of great density). On the site of the great original masses, such as Mt. Blanc, heavier internal masses were nearer the surface, and were raised up on the spot. On the contrary, where the density of the lithosphere is less, it has been accumulated by a succession of layers and has sunk down into the fluid part below in proportion to the added burden, the

upper regions of the barysphere being driven back laterally. We should thus expect to find the vertical attraction, that of gravity, stronger near the great primary masses than on the regions formed by the accumulation of layers, and this is what observation confirms. So, reciprocally, the study of the values of gravity will enable us to distinguish between one or other of these two categories of country.

The study of the local anomalies exhibited by gravity has thus an enormous importance from the point of view of the constitution of the subsoil. This subject has been carried to a quite unexpected degree of precision by the work and methods of the famous Hungarian physicist, Baron Roland Eötvös, in the course of the last ten years. He endeavoured to find what was the form of a surface normal in every point to the real directions of the vertical, the minutest deviations of which he has managed to disclose. His apparatus consists of a torsion balance with a unifilar suspension enclosed in a copper cage having double walls; the system has a very considerable period of oscillation, which extends to about twenty minutes. The oscillations of the horizontal bar were observed in two successive perpendicular planes and from this Baron Eötvös showed that it is possible

to calculate mathematically the principal radii of curvature of the unknown surface whose form is required. That being done, he took a second instrument in which the equal weights, suspended from the extremities of the oscillating lever, are no longer in the same horizontal plane, but are at different levels, one of the weights hanging below the lever, on a thread. This arrangement enables the variations of the force of gravity along the unknown surface to be measured.

By the aid of these torsion balances, Baron Eötvös succeeded in showing that the mountainous slopes of Buda were prolonged under the soil of the town of Pest, for which purpose the pendulum lacked sufficient sensitiveness and precision. He has also been able to prove variations of level in the Hungarian rivers and lakes; in the case of the Danube he was able to demonstrate such variations about 100 metres from the bank.

As to the systematic anomalies, they seem to follow laws which may be elucidated by dividing the observation stations into three categories. First, continental stations, situated in the midst of continents; secondly, insular stations, situated upon islands, in the middle of oceans, and, thirdly, coast stations, lying near the line of separation of a continent and a sea.

Generally speaking, continental stations, for example those situated on the Thibetan plateau, in the centre of Asia, show a deficit of gravity as compared with the theoretical value. Conversely, insular stations surrounded by a mass of water of less density exhibit an excess of gravity over the calculated value. At the Sandwich Islands, to take a particular example, the excess difference reaches $\frac{1}{2000}$ part of the theoretical value of gravity, and the extraordinary magnitude of this irregularity has given rise to numerous hypotheses. One of these supposes that, taking into consideration the immense extent of the Pacific Ocean, its waters are banked up on its two shores by the attraction exercised upon them by the Asiatic and American continents, so that in the central region there would be a compensating lowering of the sea-level. This would explain the anomaly, because the sea-level at the Sandwich Islands would be nearer to the Earth's centre than would be the case if no such lowering existed. This hypothesis is ingenious, but unfortunately if the experimental data be worked out it is found that in order to produce the above-mentioned difference of $\frac{1}{2000}$ part of the entire value, by approaching nearer the Earth's centre, a lowering of the level of the Pacific by more than 1200 metres

[¾ of a mile] would be required. We are not able by any measurement to prove this lowering of the level of the open ocean.

As to the shore stations, there is usually an excess, though on some shores a deficit. It is a remarkable fact that along any one coast the difference between observed and calculated values has always the same sign.

It has for a long time been believed that the excessive attracting force experienced on oceanic islands is only a particular case of a general excess of gravity existing at the surface of the oceans. Dr. Hecker of Potsdam has attempted gravity determinations at sea by the hypsometer method. We have seen that the precision of this hypsobarometric method does not exceed $\frac{1}{40,000}$ or $\frac{1}{50,000}$ part. Dr. Hecker has shown that, to this degree of approximation, the force of gravity is sensibly normal in the Atlantic between Lisbon and Bahia. On the other hand, he has proved large local anomalies on the Pacific, reaching as much as $\frac{1}{5000}$ and even $\frac{1}{3000}$ part, some positive (south of Australia and in the Honolulu roads) and others negative (above the depths round the Tonga Isles, which surpass 9000 metres [5.6 miles]). Over the rest of the Pacific Ocean, gravity seems to be normal. Nevertheless these

results indicate serious anomalies in the distribution of the intensity of gravity in the Pacific.

The real form of the geoid will not be fully known until we can measure gravity at sea with as great a precision as can now be attained on land, since the land surface covers scarcely a quarter of the surface of the globe and the form of the geoid is, therefore, unknown for three-fourths of its extent.

If continuous and precise experiments should enable rigorous measurements of gravity to be made on the oceans, and if these showed that the excess values exhibited on the oceanic isles were a general fact and applied to the entire oceans, and furthermore if a similar certainty could be arrived at with regard to regions in the midst of the great continents, such as the Asiatic plateau, viz., that the value of gravity is always in deficit there, the beautiful hypothesis of Lippmann, relating to the constitution of the terrestrial crust, would be of great importance.

We have already said a few words about this hypothesis; at the commencement of the solidification of the crust, the first solid scoriæ floated on the surface of the still liquid spheroidal bath, each one being sustained by the Archimedean thrust exerted on it by the liquid. In the case

of those pieces surmounted by mountains or heavy continental masses the weight, being relatively more considerable, would cause them to sink lower and they would accordingly plunge more deeply into the mass of liquid material on which they floated. On the other hand, those which carried an ocean, of relatively slight weight, would not sink in so deeply. In other words, the terrestrial crust ought to be thicker under the continents than under the oceans.

The general anomalies of gravity would thus be explained; under the continents the greater thickness of the crust, increased by the height of the superincumbent mass, would render the distance from the surface of the soil to that of the barysphere greater, and it is the barysphere, the nucleus of very great density, which gives rise to the greater part of the attracting force. This, being inversely as the square of the distance, would consequently be reduced for points of the continental surface. Also this diminution is not compensated by the additional attraction exerted by the continental mass itself, for that has only the density of its constituent rocks, 2.5 times that of water, while, as we have seen, the density of the central nucleus, the barysphere, is much higher.

As regards the oceans, on the contrary, the relative thinness of the crust results in the barysphere being much nearer to the geographical surface and consequently exerting, at that surface, an attractive force of greater intensity. In this way, the excess of oceanic gravity, always assuming it is proved, would be readily explained. Thus, the future of the study of gravity lies on the sea as also does that of other sciences, meteorology in particular. This should not be surprising, considering the extent of the water superficies and its uniform, homogeneous and regular surface. It is natural that the general laws to which the Earth is subject apply fundamentally to these great liquid areas.

In any case, the real geoid, after all we have just said, is not an exact ellipsoid, but one modified in places by local anomalies which produce protuberances or hollows as the case may be; the differences between the two surfaces are not very considerable, since the German geodesist Helmert has shown that the real geoid never deviates more than 200 metres [656 ft.] from the theoretical ellipsoid.

We have seen, in the course of the pages of this chapter, how the Earth's attraction produces at the surface the continual phenomenon of the fall

of bodies towards the centre. Each such fall has an effect on the intensity of gravity at the surface of the globe. When I raise a weight a small height in my laboratory in Paris and let it fall, I change at the same moment the intensity of gravity at Honolulu, and, in general, over all the Earth's surface, for in allowing the body to drop to the ground I add the attracting mass of this body to that of the terrestrial spheroid.

Another cause of the variability of gravity is thus adduced. It is true that the variation from this cause is infinitesimal, and so cannot be experimentally shown, but nevertheless it is real. The variability of gravity from other reasons is sufficient to confirm the idea of the law of instability, change, and general evolution which governs the existence of the planet on which we live.

There is still another cause of variation of gravity, which produces a secular variation. At the present time this variation is insensible, though it must have been large on taking into consideration the change in our globe since the time of its formation. The cause here referred to is the contraction of the globe due to its cooling process.

The force of gravity acting on a body placed on the surface of the Earth is in inverse proportion to the square of its distance from the Earth's centre, that is to say, in general, to the square of the terrestrial radius. If, therefore, the radius decrease owing to cooling, the force of gravity will increase accordingly.

A contraction of one-fifth part of the radius would produce an increase in gravity of $\frac{9}{16}$ of the value of the latter, in other words a little more than 50% of the value.

The hypothesis of a shortening of the radius of our globe agrees well with the fact of the foldings of its crust. Gravity at the Earth's surface has consequently increased. The importance of this fact is considerable in connection with the pressure of the atmosphere which, formerly, must have been much less than at present, in the same conditions of temperature. Even the composition of the atmosphere must have changed from this cause and would vary in proportion to the contraction of the Earth as cooling unceasingly continued.

Since this cooling, though now quite insensible, yet goes on, the slow contraction is still occurring and the force of gravity at the surface of the globe consequently increasing.

To conclude, this force, which was formerly stated to be constant in magnitude and direction, is, on the contrary, subject to continuous variation, both as regards time and space.

# CHAPTER VI

## THE RHYTHMIC MOVEMENTS OF THE EARTH'S CRUST. DEVIATIONS OF THE VERTICAL

IN our study of the Earth's movements, we have seen how great is the complexity of the motion of any given point upon its surface; we have also demonstrated and sought to explain the continuous displacement of the Earth's poles. But, in all this account, the Earth has been assumed to be rigid, and to retain always the flattened ellipsoidal form imposed upon it by the combined laws of universal attraction and centrifugal force.

But perhaps the Earth is not really rigid. The crust may not be truly undeformable. It is possible that it suffers deformation under certain influences. We have to inquire whether this is so and under what conditions such non-rigidity becomes manifest, also its extent and importance.

In the course of this chapter, we shall find that the crust is in a state of perpetual movement and incessant vicissitude which still further emphasises the life, figuratively speaking, of the Earth.

The illustrious English physicist Lord Kelvin was the first to suggest the question whether the Earth is an undeformable solid, or if, on the contrary, it is an elastic body whose form is incessantly modified by exterior causes, in particular by the combined periodical and variable attractions of the Moon and the Sun. The problem resolves itself into finding proof of the elasticity of the terrestrial crust and the measurement of such elasticity.

Any body whatever, that is free to move at the Earth's surface, for example, the heavy ball of a plumb line, is always subjected to the attractive forces exercised upon it by the Moon and the Sun. The prolongation of the plumb line should therefore describe some kind of curve on the ground beneath it. If the Earth were rigorously rigid and undeformable, it would not change its form under the action of these attractive forces, the only effect of which is to impress upon the Earth the movements of rotation, revolution, precession, nutation, etc., which have been described in detail in Chapter IV.

Assuming the Earth to be strictly rigid, what would be the value of this luni-solar attraction? At first sight, it would seem a large one. The Sun has a mass about 325,000 times greater than the Earth and is at a distance from the latter

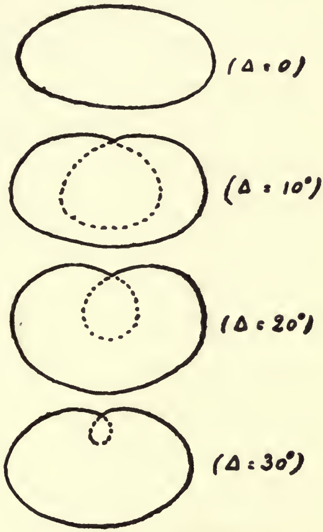
equal to 23,400 terrestrial radii. If we evaluate the attractive force strictly according to Newton's law, viz., as proportional to the product of the masses and in inverse ratio to the square of the distances, a result is obtained which is about 1300 times less than that of gravity [at the Earth's surface.—*Ed.*]. Consequently the luni-solar attraction is sufficient to produce an apparent diminution of the weight of bodies here equal to $\frac{1}{1300}$ part of their real weight.

But it must not be forgotten that the Earth, under the action of the solar attraction, executes its orbital movement. Now it is a fundamental principle in mechanics that a force already obeyed does not enter into play except as regards the effect already produced. A heavy body, suspended at the Earth's surface, and which the solar attraction tends to draw aside from the vertical, is already moving with the whole Earth under the influence of that attraction. There would consequently only remain, as an effective deviating force, the difference between the attractive force at the surface and that at the centre of the Earth. The result so obtained is, for the Sun, nearly 20,000 times less than that above given and is equivalent to only the $\frac{1}{26,000,000}$ part of the force of gravity [at the Earth's surface.—*Ed.*].

The small mass of the Moon is largely compensated, from the point of view of the extent of attractive force it exercises on a body placed at the surface of our globe, by its much greater proximity; the Moon's centre is only distant sixty terrestrial radii from that of the Earth. On applying to our satellite the same reasoning and the same calculation that we have already done in the case of the Sun, we obtain the result that the perturbing effect of the lunar attraction produces a diminution of gravity [at the Earth's surface.—*Ed.*] of about $\frac{1}{12,000,000}$ part. As the arc corresponding to an angle of a second is about $\frac{1}{200,000}$ it is evident that the deviation from the vertical due to the influence of the Moon attains about $\frac{1}{60}$ of a second.

We are indebted to Victor Puiseux for the complete analysis of this perturbing action. At a later date Gaillot put it into a simplified form and Radau made a more elementary calculation for the case where the Moon is in the plane of the equator. The astronomer Gaillot has traced the theoretical curves which the prolongation of a plumb line should describe on a horizontal sheet, under the influence of the lunar attraction, the Earth being assumed absolutely rigid. These curves are shown in the accompanying diagrams

(Figs. 14, 15, 16, 17). It will be observed that they differ in accordance with the Moon's declination, or in other words, with its angular distance from the equator.




Figs. 14, 15, 16, 17.—Curves theoretically described by the Bob of a Plumb-line, varying in Accordance with the Declination of the Moon.

When these results were known, and the minuteness of the quantity to be measured, in order to prove the diurnal variations of the vertical, realised, many physicists gave up hope of achieving it. But others attempted to overcome the difficulties of the experiment. In 1873, Zöllner tried, for the first time, a horizontal pendulum, to which we will return later in fuller detail, and which had extreme sensitiveness; in 1874, Bouquet de la Grye used a pendulum, connected with an amplifying balance, at Campbell Isle where he had gone to observe the transit of Venus; and in 1878, Lord Kelvin made use of a long pendulum the deviations of which were multiplied by means

of a small rotating mirror. In 1879, G. and H. Darwin perfected this apparatus by immersing it in a liquid bath to preserve it from disturbing effects; in 1881, d'Abbadie installed in his observatory at Hendaye, an auto-collimating telescope directed perpendicularly downward on a bath of mercury placed at the bottom of a deep shaft; the variations from coincidence of a reticle at the focus and its reflected image should be double the variations of the vertical. In 1883, Professor C. Wolf, of the Sorbonne, set up an analogous apparatus, but a horizontal one, in the vaults of the Paris Observatory; and finally, in 1890, in the same place the mining engineer Léon and I attempted to arrange a very sensitive instrument, with communicating liquid baths, the differences of level of which were observed by interference fringes in yellow light. In spite of the extreme precision of the method employed, our apparatus gave no more clearly affirmative results than those of our predecessors.

The phenomenon to be measured is extremely small. A pendulum 100 metres [330 ft.] long would be very difficult to make, and especially to set up and maintain in the necessary conditions of stability and freedom from disturbing effects. Yet even with such a pendulum the deviation in

question would be only about $\frac{1}{100}$ of a millimetre [$\frac{3}{10,000}$ in.]!

There is, however, another cause for the lack of success, and this is to be sought for in the elasticity of the Earth.

The mathematical considerations which serve as the base of the preceding experiments all depend upon the hypothesis that the earth is rigid and undeformable; if the Earth has sufficient elasticity to be susceptible to deformation under the influence of luni-solar section, the whole is changed. The entire Earth will then behave similarly to what we already know occurs in the case of the free surface of the oceans, in other words the lithosphere or solid part will exhibit the phenomenon of tides just as the seas do under the influence of the same forces.

These deformations, which the solid part of the globe suffer, are of two quite distinct kinds; one only affects the superficial layers of the crust while the other acts on the whole body of the Earth. The first is characterised by an apparent deviation of the vertical with respect to the ground; in reality, as the deformations affect the superficial layers of the Earth, it is the ground which suffers displacement relatively to the vertical, which remains fixed. Consequently the

deviations are only apparent. The principal cause of these apparent deviations is to be sought in the heating of the surface layers of the Earth by the solar rays. These rays warm the terrestrial globe just as the spirit lamp heats the copper ball in the classical experiment of Gravesand's ring. Since the surface rocks and layers have but slight conductivity for heat, only that part of the Earth turned towards the Sun is affected by the heating action and so only this part is expanded and hence deformed; the antipodes of these regions are not reached by the solar warmth until twelve hours later. For the same reason, viz., the feeble thermal conductivity of the soil, the movements of deformation thus produced are transmitted with difficulty in a downward direction and their amplitudes decrease very rapidly as we penetrate below the surface of the ground. In the Astrophysical Institute of Potsdam, under the direction of Professor Helmert, the apparent oscillation of the vertical has been found to have, at the bottom of a shaft 25 metres [83 ft.] in depth, only $\frac{1}{8}$ of its extent at the surface level of the ground.

The heating caused by the solar rays being the principal cause of these superficial deformations, which produce an apparent oscillation of the direction of the vertical, it follows that such oscil-

lations should have an essentially diurnal period; furthermore there should be another period, an annual one, due to the greater or less obliquity of the solar rays, caused by the variation in the Sun's declination according as it is above or below the celestial equator. This period is superposed on the first one and the actual resulting period is a combination of the two.

The second kind of deviation of the vertical is a true one and not only an apparent one; its cause is to be sought in the attractive forces exerted by the Sun and the Moon on the matter which constitutes our Earth.

If the Earth were perfectly rigid, absolutely undeformable, and totally devoid of elasticity, the luni-solar attraction could not produce any possible deformation of it, and in this case the oscillations of the vertical under the influence of these forces could be calculated as previously explained. If the Earth, in its entirety, were perfectly fluid, that is to say, if it behaved as a perfect, and not a viscous, liquid, the exterior surface would have a regular form, which would change continually under the influence of the luni-solar attraction. In these circumstances it would be impossible to prove the slightest change in the vertical, since by definition the terrestrial

surface, the fundamental surface, of elevation, would always be normal to the direction of the plumb line. Consequently the terrestrial tides, the deformations, while attaining the greatest amplitude theoretically possible, would not be demonstrable, for lack of reference points, just in the same way as the oceanic tide cannot be appreciated by a navigator in the open sea, out of sight of land, the sea being assumed to be too deep for precise soundings, which would otherwise prove differences in the depth of the water, to be taken.

But in reality the terrestrial globe is very far from being a perfect fluid. Without being absolutely rigid, it has a considerable degree of hardness. The molten material constituting the internal magma is subjected to such pressures that the state it exists in is hardly conceivable to the mind, which in the attempt to realise it is obliged to picture conditions of which it has had no practical experience. Nevertheless by a rigorous analysis of the question based on the known values of the precession of the equinoxes and of nutation, Lord Kelvin has found that the Earth, taken as a whole, has a rigidity sensibly equal to that of steel. This result is by no means incompatible with the state of fusion of the metals constituting the cen-

tral nucleus, since this state is largely counteracted by the formidable pressures to which they are subjected. We may therefore admit that the terrestrial globe, taken in its entirety, possesses a certain elasticity.

Owing to the facts of this elasticity and the luni-solar attraction, the form of the globe will be modified. At the same time, the action of the igneous matter will deform the superficial layers, and the deviation which may be shown relatively to the direction of a plumb line will therefore be only that due to the difference of these two effects.

This explains the lack of success of the experiments described above; all were made on the assumption of the absolute rigidity of the Earth with the object of verifying the extremely slight variations of the vertical, which were of theoretical interest. The non-rigidity of the ground diminishes these minute variations still further, hence the failure of methods and apparatus to show it that were hardly sensitive enough even if the Earth had been quite rigid.

The credit of having demonstrated these deviations, not only qualitatively but even quantitatively, falls to Dr. Hecker, of the Geodetic Institute of Potsdam. For this purpose he utilised the wonderful sensitiveness of the horizontal

pendulum, an instrument constructed several years before by von Rebeur-Paschwitz, which reached a high degree of perfection, but was still further improved by Dr. Hecker. The horizontal pendulum (Fig. 18) is an instrument of extreme sensitiveness. It is composed essentially of a horizontal rod T, fixed by two vertical threads F and F′ to a strong support S; the points of attachment A and A′ are not exactly one above the other, but they may be made as nearly so as is desired. A mass M is fixed at the end of the lever T. In these circumstances the pendulum takes a position of equilibrium for a given direction of the vertical, but, if this latter should change, the pendulum begins to oscillate with a period the same as that which a simple pendulum would have if of length equal to the distance between the mass M and the point V where the vertical M V intersects the straight line joining the points of attachment A A′ of the two threads. It may be seen by an inspection of the figure that we are able to make the length M V as great as is desired; all that is necessary is to place the points A and A′

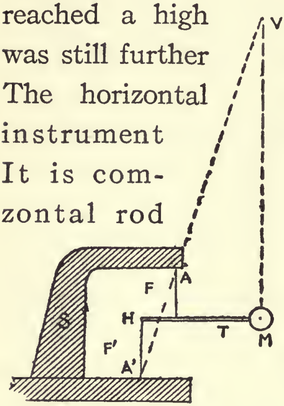



FIG. 18.—Principle of a Horizontal Pendulum.

more nearly above one another. We thus have a horizontal pendulum H M which oscillates with the same period as a vertical pendulum of very great length V M N and we may make the length of the equivalent simple pendulum so great that its oscillation may show the little displacements from the vertical which we have previously described.

Dr. Hecker took two of these pendulums, the shafts of which were perpendicular to one another; their lengths and the relative positions of the points of attachment had been regulated so that they corresponded respectively to simple pendulums of 175 and 117 metres [574 and 384 ft.] in length. The shafts were orientated symmetrically with regard to the meridian of the place. Two mirrors fixed on the shafts enabled the period of the oscillations to be registered photographically on films, the distance of which further increased the amplitude of the deviations, and this was already doubled by the reflection from the mirror.

By taking the photograms thus obtained and constructing graphs from them by points, having for abscissæ and for ordinates the results deduced from the movements of the two pendulums, a curve results which illustrates the displacement of the point of a plumb-line, that is to say of the

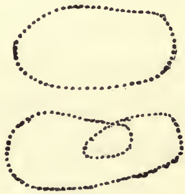
deviations of the vertical; such a curve has been constructed for every day and the results have been collected in groups of ninety days to furnish three-monthly averages.

A diurnal oscillation of the vertical to the extent of two-thousandths of a second of arc in the direction of the meridian has thus been distinguished; furthermore the three-monthly averages have shown that the amplitude of the oscillation is only half in winter what it is in summer. As Lallemand has justly observed, this is a clear indication of a thermal effect produced by the heating of the peripheral layers of the Earth's surface under the action of the solar rays and "these effects overlie those of the attraction of the Sun on the pendulums and almost mask them entirely."

Dr. Hecker has, however, been able to demonstrate the latter because of the fact that the period of the thermal effect is twenty-four hours, that is to say, is diurnal, while for the purely attractive solar action the period is twelve hours, that is to say, semi-diurnal. The attraction is exercised similarly whether the point in question is directly opposite the Sun on the near or far side of the Earth and therefore makes itself evident twice in every twenty-four hours. By combining the values of the deviations for corresponding hours of the

two unsymmetrical periods of twelve hours each, and taking the semi-sum and the semi-difference of the deviations for each pair, the result sought is obtained, for in the semi-sum the thermal effect is naturally eliminated, since it is equal and of contrary sign in the two terms, while the attractive effect is not so counterbalanced. It is the contrary as regards the semi-difference, which isolates the thermal effect by eliminating the attractive one.

In the case of the lunar action, the separation of the two effects is more easily made on account of the difference of the periods of the solar day and the lunar day. Dr. Hecker has been able to construct the experimental curve which the point of a plumb-line describes under the Moon's influence, by a graphical interpretation of his observational results.



Figs. 19 and 20.—Real Curves described by the Bob of a Plumb-line.

This curve is shown by a dotted line (Fig. 19). Fig. 20 represents the same curve in the case where the declination of the Moon is a high northern one. The exact resemblance of these experimental curves with the theoretical ones given by Gaillot, and reproduced in Figs. 14 and 16, is very

striking. The only difference is in the lesser amplitude of the real curves. The diminution of amplitude is almost twice as great in the direction of the meridian as in that of the east-west direction at right angles to it; it reaches nearly half in the direction of the meridian. The little closed loop seen on the two curves corresponding to high declinations of the Moon arises from the fact that there are two daily maxima; these maxima are equal if the Moon is in the plane of the equator; inequal if it is to the north or south of the equator, the more so as it is farther away from the equator.

The difference between the calculated and observed curves, assuming that the latter give similar results when the enquiry is pursued over a longer space of time, shows that the Earth, taken in its entirety, possesses a certain degree of elasticity which is of the same order of magnitude as that of steel. In other words the Earth behaves almost as if it were made of solid steel, and of its present dimensions. It is especially remarkable that the consideration of the oceanic tides, the astronomical movements of the Earth, and the displacement of the terrestrial poles all lead us to assign an elasticity of the same order of magnitude to the Earth taken as a whole; it is an admirable confirmation

of the original idea of Lord Kelvin. There is only one point that remains obscure in the interpretation of Dr. Hecker's results, viz., the reduction of the amplitude of the deviations in the direction of the meridian, a reduction of the extent of the phenomenon to almost half its value, while there is scarcely any such reduction in the east-west direction. In the masterly analysis of this question that he has made, Lallemand has sought the cause of this anomaly. It may be due to the instrument itself, or to the relative proximity of the sea, or to a peculiarity of structure of the Earth's crust in the Potsdam region, or again to the tetrahedral form of our globe, of which the Eurasian arête, oriented in the east-west direction, passes not far from Potsdam. Lallemand favours this last suggestion. In spite of this incompleteness of our knowledge much has been achieved; we know that the globe taken as a whole has an elasticity of the same order of magnitude as that of steel, and we shall see later on that the study of the seismic phenomena brings further confirmation of this fact.

As a result of our study of the combined action of gravity and the luni-solar attraction on a plumb-line we can deduce another consequence; the thread which supports the mass cannot be recti-

linear, but has the form of a curve, the equation of which has been given by Puiseux. This curvature has not been detected by any of our methods of measurement so far, but we know that it exists. Since a stretched horizontal thread, however fine it may be and however well it may be stretched, is never rectilinear, because of gravity which imposes upon it the form of a catenary, it will be seen that a straight line is not realisable, at any rate mechanically. It is also the same optically; light, because of the movements of the Earth, and because of refraction and diffraction, is not propagated in a straight line. The idea of a luminous ray has given place to that of a wave. The edge of a crystal is not a right line, for during the time that a second molecule has taken to align itself with the first, the Sun and the Moon have changed position relatively to the Earth and have deviated the molecule from the position it would otherwise have taken.

Is the straight line then entirely a creation of Man's brain? If so, he might be justly proud of it.

However this may be, everything about our Earth is in continual movement, in spite of the deceptive appearance of stability presented to us. The crust expands and contracts under the daily action of the solar heat; the nucleus, rendered

dense and compact by the pressures acting upon it, is subjected to veritable tides under the influence of the luni-solar attraction and we may be certain that the fluid layer, interposed between the nucleus and the crust which covers it, is agitated by perpetual movements, both of tidal and convective origin. Where then may we find real stability? Where is the invariability which the rocks seemed to symbolise so well? In the imagination of poets perhaps, but not in the reality of Nature, where everything moves perpetually. The different forms of movement we have hitherto dealt with, whether affecting the entire Earth or only its crust, are of astronomical origin. We now come to movements of a different nature, viz., the sudden movements which sometimes disturb a large extent of the Earth's crust, known as earthquakes, and also the slow continued movements which produce the raising and lowering of the crust.

## CHAPTER VII

### THE SUDDEN MOVEMENTS OF THE EARTH'S CRUST. SEISMIC PHENOMENA

WHEN the terrestrial crust was formed by the solidification of the superficial layers of the nucleus of fused matter, the spheroidal form of which constituted the Earth at the commencement of its history, a colossal reserve of energy was imprisoned inside it. This energy results from the heat of the central nucleus, which exists at inconceivably high temperatures.

Now the crust is far from homogeneous; it was not formed all at once, but in pieces of which the earlier ones constituted scoriæ, isolated and floating on the surface of the spherical liquid mass. These became gradually united with each other and, being of various thicknesses, thus formed the first irregularities of the Earth's crust, which, as previously stated, has been likened by Lapparent to a marqueterie. Its lack of continuity and homogeneity involves an important consequence;

if we compare it to a boiler, this boiler will not be equally strong everywhere but will have weak places in its sides, flaws as they are called in metallurgy, and it will burst at these places if the interior pressure increases beyond a certain limit.

The internal energy may manifest itself by the upward expansion of the material forming the superficial layers of the central nucleus, through a fissure in the crust. Such a manifestation constitutes a volcanic eruption.

As regards the cause which makes this material rise up through the fissures and fractures of the crust, it is probable that under the influence of the progressive cooling of the nucleus, a cooling which although very slow continues incessantly, gases are given off from the still liquid upper layers of the internal part, and accumulate under the crust, upon which they consequently exert a pressure. Possibly, also, the water of the seas infiltrates through the crust, which is of less thickness under the seas than under the continents, as we have already seen; such infiltration would lead to the contact of the water with the igneous masses and the consequent dissociation of the water into its constituent gases. This would be another cause of an increase of internal pressure, tending to

break open the crust and let the gases and the igneous material shoot out, or in any case to disturb violently the sides of the boiler, so to speak, which the terrestrial crust forms. The thermal energy accumulated at the centre can thus manifest itself exteriorly in two distinct ways: either by an expansion of the inner liquid and gaseous material and the forcing of this through the crust which the pressure has made to yield at some point; or by sudden movements and agitations imparted to the crust, by the internal pressure, which moves or bends the crust without breaking it, this sometimes resulting only in a vibratory phenomenon transmitted as true waves. The first is a volcanic eruption; the second a seismic phenomenon. Volcanoes and earthquakes are consequently two manifestations of the same cause, but they are in no wise directly connected together. As an example, in the case of Japan, which is the classical earthquake country, so to speak, the internal activity which is constantly manifested by very frequent earthquakes does not awake the old volcano of Fusiyama from its long quiescence.

The general characteristic of a volcano is that it occupies the summit of a mountain and gives off permanently, or at intervals, a greater or less abundance of vapours; from time to time out of

an opening whose mouth is at the summit, and which is called the crater, it ejects a rain of stones and cinders accompanied by thick clouds of vapours and sometimes by burning gases. Such were the thick burning clouds observed at Martinique during the courageous and profitable study which Professor Lacroix made of the volcano, Mt. Pelée. These clouds are often the seat of violent electrical manifestations and are, consequently, furrowed with lightning flashes. While these emissions of gases and vapours take place into the atmosphere, a river of fused rock and similar materials, called lavas, emerges from the crater, streams down the sides of the mountain, and covers the surrounding country, sometimes to a considerable distance, retaining for a long time a very high temperature.

The volcanic mountains have been formed by such lavas and eruptive rocks. The first eruption takes place through a fracture in the crust; the rocks and lava accumulate around the orifice as an ever-increasing cone, since each new eruption expels new material onto the flanks of the small mountain so formed, increasing at the same time its extent and height. Little by little the cone becomes a mountain, which remains pierced with a passage traversing the crust, called a funnel,

preserving communication between the exterior of the crust and the fluid incandescent magma which forms the upper part of the central nucleus. It is the extremity of this funnel which is called the crater.

When a volcanic mountain attains a certain height, for example over 4000 metres [13,000 ft.], as is the case with Mauna Loa in the Sandwich Isles, it needs a great pressure to support and eject the high column of lava which fills the funnel. For such an eruption to take place, the cause of which we have already spoken must operate, viz., the setting at liberty of enormous quantities of gases in the upper part of the interior magma. These gases result from the effervescence of the fused masses and are expelled violently through the orifice open to them, being forced out in consequence of their extreme pressure. In the case of Mauna Loa, the mountain stands on the floor of the Pacific and rises, as stated, to a height of more than 4000 metres [13,000 ft.] above sea-level; the gases which eject lava to its summit must therefore exert a pressure of several thousand atmospheres. These lavas constitute a veritable lake of fire in the great crater which exists at the summit of the mountain; they overflow and spread in great rivers of fire down the sides of the gigantic

cone. We have here a typical case of a continuous outpouring of lava. Such a volcano is a true safety valve in this region of the Earth's crust.

But other kinds exist which are subject to frequent eruptions, notably the European volcanoes such as Vesuvius and Etna. When the lava arrives at the summit, already cooler and in less quantity, or when after an eruption, there is a slackening in the upward propulsion of the fused matter, that which fills the upper part of the crater solidifies, and the internal energy can then manifest itself again only by the emission of more or less abundant gases and vapours, which are prevented from escaping by the mass blocking the funnel of the volcano, and so accumulate under the crust. Since the pressure gradually increases, sooner or later it becomes greater than the obstructing mass can sustain. The eruption, therefore, has the character of a veritable explosion and often the entire mountain bursts like a shell does under its charge of melinite. The debris of the explosion is projected high up, ashes being carried to a height of several kilometres [or miles], and rocks are flung on to the surrounding country for a distance of hundreds of kilometres [or miles]. The eruption in this case always attains the character of a catastrophe; it will suffice to recall the eruption

of Mt. Pelée in June, 1902, and that of Krakatoa, in the Sunda Isles in 1883. In cases where the volcano rises directly out of the sea, constituting a small island, the latter may entirely disappear in the course of the cataclysm; often, however, it only partially disappears, leaving only the crater above the sea-level. In this case a pierced or broken portion frequently admits the sea to the interior of the crater, thus forming an almost closed bay as may be seen in Saint Paul Island, in the Southern Seas. This crater-isle has been carefully studied by Professor Vélain. The Greek Archipelago has often been the seat of similar cataclysms, for example that of Santorin.

The mass of material ejected by volcanic eruptions may attain considerable proportions. This is obvious from a consideration of the volcano in the Sandwich Isles, before mentioned, when we recollect that the mountain itself, more than 4000 metres [13,000 ft.] high, is formed by material ejected during successive eruptions, and accumulated as a cone around the original orifice. The island itself, which is entirely constituted of lava, forms a mass of more than three hundred thousand cubic kilometres, since the cone is continued downwards under the water to the submarine floor of the Pacific. Even Vesuvius, one of the

smallest of volcanoes, has given forth streams containing fifteen and twenty millions of cubic metres [or yards] of lava. The statement of these quantities, if we remember the considerable number of craters that are active at the present time and also the very large number of extinct volcanoes, shows that the exterior appearance of the Earth is incessantly modified by the addition of new material which alters its relief and strews its surface with mineral matter brought from the interior of the globe.

For a volcano to come into being, there must initially be a cleft, fissure, or crack in the terrestrial crust. Now there are regions of the Earth which are especially prone to such fractures, viz., the border of the oceans, chiefly those where an elevated coastal region dips suddenly to the sea. The seas, in fact, mark the lowered portions of the kind of marqueterie formed by the terrestrial crust while the continents represent the raised portions.

Maritime shores are therefore volcanic regions, places given over to volcanic activity; it is only necessary to glance at a map of the world (Fig. 22, p. 215) for direct confirmation of this fact. The Pacific is bordered everywhere, even on the shores of the Antarctic continent by a girdle of active volcanoes

which constitute a veritable fiery circle; so also a long chain of volcanoes lies along the shores of the Mediterranean, and extends by Asia Minor and the Persian Gulf to the Sunda Isles. Another line of craters lies in the midst of the Atlantic from Jean-Mayen and Etna in the north to the Antarctic volcanoes in the south passing by the shores of the Azores, Madeira, and the Canary Islands, where stands the imposing Peak of Teneriffe whose activity has recently begun to manifest itself anew.

The number of active volcanoes actually known is to be reckoned by hundreds, and this does not include the numerous submarine volcanoes which doubtless exist beneath the oceans, especially under the Pacific and whose existence and activity are only made known to us by abnormal waves on the surface of the oceans which cover them. Besides volcanoes proper, other phenomena at various points on the Earth's surface clearly point to internal activity; geysers, hot springs, and emanations of sulphur vapour which burst through fissures in the crust bear witness to the heat energy accumulated in the interior regions below. Volcanic eruptions and gaseous emanations do not always form a sufficient vent for the manifestations of this energy, which relieves itself by means

of other phenomena that we will now study, viz., seismic phenomena.

The causes of the instability of the Earth's exterior envelope are numerous. We have noted, in the course of preceding chapters, those of them that are periodic, but there are others, the explanation of which must be sought in the situation of the crust itself in relation to the heated nucleus which it covers.

This nucleus cools at a constant rate, and in so cooling contracts. In the course of time, therefore, a space would be left between the upper layer of the nucleus and the lowest part of the crust which floats on its surface. The part of the crust which is immersed in the liquid mass below it has in all cases an upward thrust exerted upon it by this mass. Now this thrust will diminish in proportion as the internal mass contracts. After a sufficient interval of time the crust becomes insufficiently supported from below and so tends to sink down, and this sinking gives rise to a disturbance which affects a larger or smaller area around the principal centre of action. As the cause operates continually, this result will occur at all times of the Earth's history, though perhaps in a discontinuous way.

This is not all. Volcanic eruptions throw on

to the surface of the Earth's crust a quantity of material which was formerly below it; such material is not replaced and its removal creates a space below the crust and at the same time adds to the weight of the latter. Gravity consequently tends to make the surface fall in and fill up the space when the upward thrust from below is insufficient, and this constitutes another reason why the external envelope of the Earth sinks.

It is, therefore, to be expected that each such sinking will be manifested by a shock, sometimes feeble and sometimes great, according to the degree of the fall which produces it. Furthermore, currents circulate in the upper regions of the central nucleus, the part that is still fluid, and so cause waves and undulatory movements which come into contact with the parts of the crust which project below its interior surface. The force of these agitations results in the shaking of these projecting parts, and the disturbance is transmitted by them to the rest of the solid crust. There are thus numerous reasons why the crust is never in repose.

In consequence of the incessant disturbances to which the crust is subjected, the importance of the study of these sudden movements that have such a disturbing effect upon it will be obvious.

Some of the shocks are devastating, others are feeble, sometimes even so feeble that only delicate instruments called seismographs, which are always based on the principle of inertia, can disclose and register them. There are, therefore, earthquakes and earth tremors, of varying intensity.

It is customary to divide the shocks which the Earth's crust undergoes into three categories: vertical shocks which, if intense enough, may project buildings upward into the air, as if an explosion had taken place; horizontal shocks which displace objects on the ground laterally and which are capable, among other results, of displacing an upper course of masonry with respect to a lower one; and finally undulatory shocks, the most numerous and the most terrible, which spread through the ground surface in the same way as the swell of the ocean spreads through the water surface. When such a seismic wave occurs the surface of the Earth's crust is agitated and disturbed just as the waves of the sea are. But these shocks produce a permanent alteration in the solid surface, whereas the waves of the sea give rise to only a passing perturbation; numerous deep crevices appear, buildings are destroyed, trees torn up, and whole towns may be annihilated. Recent examples are Valparaiso, San Francisco, and, still

more lately, Messina, where the earthquake destroyed more than 200,000 human lives in a few seconds.

The centre of disturbance, the point from which the waves seem to radiate, is almost always below the surface of the ground, sometimes at very considerable depths, even up to 20 kilometres [12.5 miles]. This point is analogous to that where a stone thrown into water strikes the water; circular waves originate there and travel outwards. The orientation of the crevices and their inclination to the vertical enable the position of this point to be fairly accurately obtained. The projection of the centre of disturbance onto the ground surface, that is to say the place where the centre would be marked on a map, is commonly called the epicentre. The crevices crop out in the ground around the epicentre, forming concentric curves, roughly circular when there is only one centre of disturbance, but often elongated, in which case the existence of several such centres seems to be indicated. The movements are propagated at the surface of the ground with velocities varying between 150 and 800 metres [500–2500 ft.] per second; we shall see later on that the rate of propagation for the total mass of the Earth is much more rapid.

These great disturbances are happily not very frequent; it is the earth tremors, detected and registered only by means of seismographs, which by their frequency prove the continual quivering of the solid crust of the Earth. It appears that more violent earthquakes occur when the barometric pressure is low, which is easily understandable, since the terrestrial crust supports a less quantity of atmosphere than usual and so the pressure inside it is not so much opposed as usual. A barometric fall of 1 centimetre [.39 in.] produces an increase of internal pressure of 130 kilograms per square metre [285 lbs. per sq. yd.], *i. e.*, 130 millions of kilograms per square kilometre. Earthquakes are also more frequent in winter than in summer and are especially numerous at the time of the equinoxes; the eruption of Mt. Pelée, in Martinique, in 1902, accompanied by a considerable local earthquake and a tidal wave, occurred at a time when the Sun and the Moon were in a straight line with the Earth and so produced a combined attractive effect on the latter. Possibly internal tides arise forming a wave at the upper liquid surface of the central magma; it is then readily understandable that, at the period of the equinoxes, when the luni-solar attraction is greatest, the internal tide, and consequently its wave-

force, would be strongest. In this case, as M. Kovesligéthy believes, external factors would be the determining causes of the liberation of the internal energy which takes place in virtue of the weaknesses of the crust.

It is possibly in this direction that we must seek the solution of the important problem of the foretelling of earthquakes; such a result can only be attained by studying the laws which govern the movements of the superior fluid layer of the interior nucleus of the Earth, with the aid of modern physical methods, with their increasing precision. A remarkable coincidence between the years of maximum earthquakes, of maximum polar auroræ, and of maximum magnetic storms has already been demonstrated. The periodicity of the three phenomena is the same, viz., eleven years, which is also the periodicity of the maximum activity of the solar spots. Our Sun, by the attraction of its mass, is the cause of the complex movements the Earth performs; by warming the Earth's crust it produces a daily deformation of the latter; it causes tides, not only at the surface of the seas, but also at the surface of the ocean of heated lava which exists beneath our feet. The question naturally follows whether the periodical variation in the number of the solar spots produces a variation

of the kinds of radiation emitted by the Sun and what effect this would have upon the Earth. The Sun creates a field of force about it in space, and the intensity of this field is affected by the slightest variations in the solar activity. It may be, therefore, that we must make a fuller study of the Sun in order to determine the law of the vicissitudes of the Earth's thin and incessantly quivering crust. When we have described the magnetic and electrical phenomena of which the Earth is the seat, we shall still better understand the unquestionable influence that the Sun exerts on the terrestrial globe.

Seismic phenomena should not be treated as isolated occurrences, for the same reason that applies in the case of volcanic eruptions, viz., that they are different manifestations of the internal energy, having no "laws" or necessary interconnection in time or space, but they nevertheless arise from one sole cause, so some law should govern them when taken together.

The universal prevalence of seismic phenomena is established, just as in the case of volcanic eruptions. As regards the last, we know that nearly four hundred active craters exist on the Earth's surface, and that more than double this number of extinct or sleeping ones can be distinguished,

and this takes no account of the unknown number, which is perhaps very large, that the oceans cover with their vast area of water. In recent years there have been signs of awakening of many of these centres of eruption, for example, in 1909, as has previously been mentioned, the old volcano of Teneriffe, which had seemed definitely extinct has given proof of a renewal of activity.[1] A week never passes without the telegraph bringing news from some part of the world of earth movements, sometimes devastating, sometimes less important, but always clearly perceptible; especially in Turkestan, India, the Caucasus, the Philippine Isles, Japan, Sicily, and Provence, the Earth quivers and suffers incessant disturbance. Islands even disappear suddenly. We have thus isolated occurrences which are various forms of phenomena all resulting from one general cause. Lallemand has investigated whether it would not be possible to account for the seismic manifestations of the internal activity on the basis of the tetrahedral theory of the formation of the terrestrial crust, which theory was proposed by Lowthian Green in 1875. We have already said a few words about it near

[1] In June, 1914, Lassen's Peak in California became mildly active, though for many years it had been considered entirely extinct.—*Ed.*

the beginning of this work, and we must now return to it in fuller detail. The English scientist had shown that when tubes of india-rubber were compressed from the outside, these tubes instead of being flattened took a form, the section of which was a triangle with concave sides. If the air contained in a glass globe, which is softened by heat, be exhausted, the globe, originally spherical, takes a form in which four hollow faces are clearly seen, these being the regions of flattening under the influence of the relative external increase of pressure. This form of triangular pyramid, or rather the tendency to take this form, is, moreover, a consequence of the principle of least action; starting with a fixed surface area, the terrestrial crust should, nevertheless, diminish as regards its enclosed volume, since the force of gravity makes it remain in contact with the internal nucleus and since this is continually contracting as it cools. In order to enclose a minimum volume, and at the same time obey the double condition of maintaining a fixed surface area and a symmetrical form, the crust must tend appreciably towards the figure of a regular tetrahedron, *i. e.*, a triangular pyramid with equilateral faces, which is a regular solid occupying the minimum volume for a given area of surface.

It seems, however, at first sight, that the pyramidal form, with its edges, apices, and faces, is far removed from a spheroidal one, but we shall see that such dissimilarity is only apparent and that, on the contrary, the resemblance becomes marked when we study the matter more closely.

The exterior appearance of the Earth, *i. e.*, the aspect it would present to an observer placed far away from it in space, is the result of the combination of the solid crust and its aqueous envelope, or in other words the lithosphere and the hydrosphere, the barysphere or central nucleus being in the interior of the first two.

If, since the time of its definite solidification, the crust tended to take the tetrahedral form, its foldings, and consequently the general orientation of the features of its relief, would have been made under the influence of that tendency (Fig. 4, p. 32). Hence the regions near the summits of the pyramid would be the only ones emerging above the hydrosphere. Moreover it is natural to suppose that the terrestrial axis coincides with one of the four axes of symmetry of the tetrahedron; there ought, thus, to exist in one of the hemispheres three continental elevations, represented by three summits, the corresponding pole being occupied by an ocean, the bottom of which is represented by one

of the flattened faces of the pyramidal figure. On the other hand, the opposite pole would be at the fourth summit of the pyramid and consequently a continental mass would emerge there above the spheroidal surface of the oceans.

Voyages made in the polar regions, both arctic and antarctic, during recent years fully confirm these aspects of the theory. Nansen, in the course of his circumnavigation around the North Pole has shown that that region was occupied by a sea whose depth reaches nearly 4000 metres [2.5 miles];[1] on the other hand Ross, de Gerlache, Charcot, Scott, Shackleton, and Amundsen have verified the existence around the South Pole of an immense continent whose centre is occupied by a highly elevated plateau and above which rise peaks whose height surpasses 4000 metres. The diametrical opposition of the continents and seas is consequently demonstrated with remarkable clearness, as regards the polar regions.

It is equally verified by terrestrial geography as a whole; the three continents Europe, Asia, and America, widened at the north and narrowed to-

[1] Peary, in 1909, when on his successful trip to the North Pole, secured much new information about the Arctic Sea. In support of the present theory, he failed to reach bottom on his sounding made farthest north—within about five miles of the pole itself—although using a line of 1500 fathoms [9000 ft.] in length.—*Ed.*

wards the south, are separated by three oceans, narrowed in the northern parts and broadening in the southern hemisphere. It may be said that Europe and Asia are connected together in their northern parts, but this is rather a superficial objection, since beyond the Caspian Sea and the Sea of Aral obvious signs of an actual depression between these two continents exist. Also precise measurements have shown that the western half of Siberia has only a very slight elevation above sea-level; a very slight lowering of the level would transform that part of the continent into a sea. Possibly, at a not very far distant period this depression, lying along the foot of the Ural Mountains, was covered by an actual sea. The pointed terminations of the continents towards the south, Cape Horn, the Cape of Good Hope, the point of Tasmania prolonging Australia, which is itself a continuation of the Asiatic continent, indicate that the base of the terrestrial tetrahedron is towards the north. The northern widened parts of America and Asia are very nearly connected together by the elongations between which passes the Strait of Behring.

But we can carry still further the conclusions that may be deduced from this theory of the terrestrial tetrahedron. So far, we have only con-

sidered the tendency to the tetrahedral form in the case of an immovable Earth. We know, however, that the Earth is not immovable, but, on the contrary, performs a number of combined movements of which one of the most important is its movement of rotation.

What would be the effect of the Earth's rotation on the tetrahedral figure at the time when this was being formed? We shall see that it would deform the lines and produce on the solid crust a geographical modification of which indisputable evidence is found and which would be difficult to explain in any other way. A familiar comparison will lead us to understand the nature and origin of this deformation.

Let us take an old umbrella, the covering material of which has been removed, and at the end of each rib attach a little leaden ball. Then let the umbrella be opened and an effort be made to make it turn between the fingers, holding it vertically with one hand and rotating the curved part of the handle with the other; this curved part furnishes a lever arm to the motive force given by the hand. A resistance will be felt which tends to retard the rotation of the umbrella and such resistance is due to the moment of inertia of the apparatus, this tending to resist the turning force that we

apply. If we apply a too violent force to the handle in this way, we shall cause a torsion of the ribs and their supporting pieces and these will twist if their attachment be sufficiently strong to stand it.

A similar thing occurred at the time of the solidification of the crust. The emergent continental

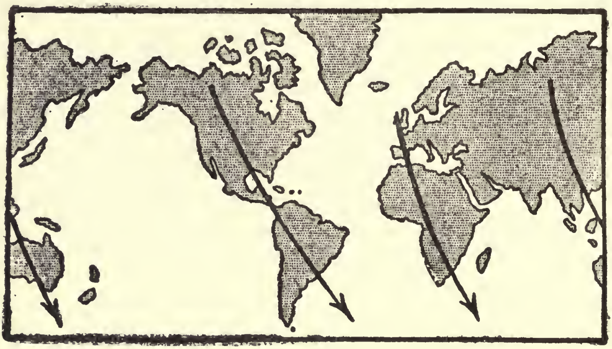


FIG. 21.—The Deviation of the Southern Continents toward the East.

apices, though acted upon by the force of rotation, remained in place by reason of their inertia. But the influence of the rotation continued to make itself felt and the edges connecting the northern continental apices with the South Polar apex (Fig. 4, p. 32) were twisted in the middle so that while the northern parts of the continents remained retarded, towards the west, their southern parts, narrowing down to points, became deflected to-

wards the east because of a common deviation. A glance at a map of the world (Fig. 21) clearly shows the fact of this deviation.

Now, in twisting, the edges of the tetrahedron became weakened in their middle points and the crust gave way there; this line of rupture actually exists, and has received from geographers the

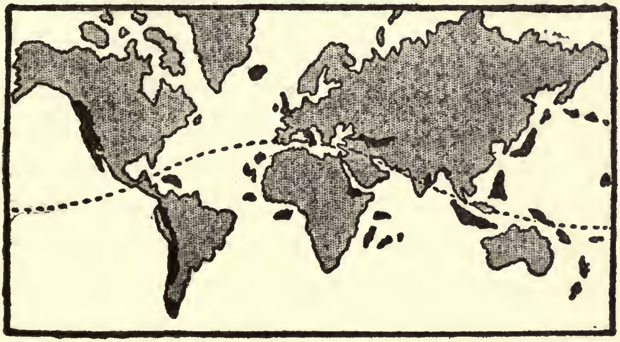


FIG. 22.—The Distribution of Volcanic Regions—The Intercontinental Depression.

name of the intercontinental depression. This depression is a kind of furrow, a marine girdle which completely surrounds the terrestrial globe nearly at its middle, that is to say in the neighbourhood of the equator, of which it is north in some parts and south in others. Europe, in fact, is separated from Africa by the Mediterranean Sea; Asia is separated from Australia by a series of seas almost blocked with chains of islands

which are mountains whose summits only appear above the waters. Finally North America is connected to South America only by the frail junction known as the Isthmus of Panama (Fig. 22).

The remarkable conception of a terrestrial tetrahedron has yet another consequence; it allows of a very simple explanation of the distribution of volcanoes and of centres of seismic disturbances on the Earth's surface.

When the interior crust, under the influence of the contraction of the central nucleus, became folded and wrinkled in order to remain in contact with the nucleus, which gravity forces it to do, the foldings showed the tendency to conform to the tetrahedral character. These foldings were formed in a still plastic crust, but later, when it became rigid, the action of the same forces tended to produce, not foldings, but fractures. Hence the continuous shocks which disturb the crust are due to its deformation.

But the regions where the foldings were produced are the regions of least resistance; if a boiler plate be bent and then made use of, the pressure of the steam will cause a fracture exactly in the place where it was bent. Now the edges of the tetrahedron and the neighbouring regions are the foldings of the crust, and so its resistance ought

to be more feeble there. The same applies to the whole length of the intercontinental depression where the crust has already suffered a twisting tending to enfeeble its resistance to rupture. The great continental ridges, such as the American Cordilleras and the chains of islands bordering the Pacific, will thus be the special regions of earthquakes and of volcanoes, the latter formed about the fissures of the folded and weakened crust. *A fortiori*, the greatest number of volcanoes ought to be situated at the points of intersection of the continental ridges with the great intercontinental depression. That this is so may be seen at once from a glance at a map giving the distribution of volcanoes over the Earth's surface (Fig. 22). The Pacific in particular is surrounded by a veritable fiery circle. On the other hand, craters are not met with on the gentle slopes whose uniform inclination shows that there have been no foldings and sudden deformations.

The mining engineer, M. Lallemand, to whom we owe the extremely precise methods of modern determinations of altitude, has shown that the tetrahedral theory also allows of a very natural explanation of the anomalies that have been proved to exist in the values of gravity. As we know, gravity is weakest in the middle of a continent

and strongest on the oceanic islands, whereas if we were guided only by the consideration of the density of the immediately neighbouring regions, the reverse should be the case.

Actually, the exterior of the terrestrial globe comprises two different things, the lithosphere which is the foundation, supporting the hydrosphere which covers the greater part of it. The latter, because of its fluidity, obeys the combined actions of gravitation and centrifugal force. If its surface be prolonged in imagination beneath the earth, as a result of the operations of determination of altitude, we arrive at a surface called the geoid, as previously stated, which is the fundamental surface of elevation in the consideration of gravity. But in the neighbourhood of the summits of the tetrahedron, that is to say, in the central regions of the great continental masses, this surface must project above the normal ellipsoid of the geodesists, for the tendency to the tetrahedral form manifested by the lithosphere since its original solidification ought also to be found in a smaller degree, in the fundamental surface of elevation. Consequently there should be corresponding irregularities in the values of gravity reduced to sea-level, that is to say, after allowance has been made for the attraction of the subjacent

crust. In the neighbourhood of the edges of the tetrahedron, rising above the theoretical ellipsoid, the attractive force ought therefore to be weaker and the centrifugal force stronger than in the middle of the oceans, where the stronger attraction and the weaker centrifugal force produce, on the contrary, an excess of gravity. This excess in the oceanic islands and the deficit in the interior of the continents are shown by actual experimental results.

This new explanation due to M. Lallemand is in complete accord with the theory of Professor Lippmann. It is also another confirmation of Lowthian Green's conception of the terrestrial tetrahedron. One last source of confirmation has not yet been realised, but will certainly be so sooner or later, thanks to the efforts of the International Geodetic Association, viz., the measurement of three long meridian arcs in the southern hemisphere, as near as possible to the South Pole and in particular in the Argentine and the Antarctic continent. If the Earth has really tended to a tetrahedral form in becoming externally solidified, and considering, besides, the large proportion of water and the small extent of land in this hemisphere, it may legitimately be supposed that the flattening of the Earth will be a little less in the

southern hemisphere than in the northern one. The greater number of the long meridian arcs on which geodesists have centred their efforts during the last century and a half are situated in the northern hemisphere. The Peru arc, measured in the eighteenth century by Bouguer and La Condamine, and remeasured recently with great trouble and remarkable precision by the equatorial mission under the direction of Colonel Bourgeois, and the arc of the Cape of Good Hope, the work of English astronomers, are the only ones furnishing us with data for the southern hemisphere. It is to be hoped that a continuous arc, from Cape Horn to the equator, will soon be measured in South America. Then we shall perhaps have the ultimate data that we lack, in default of a method and instrument permitting navigators to measure the intensity of gravity with precision on board ship in the open sea, in the regions of the geoid where, up to the present, all accurate results have been found impossible.

The scientific observation of earthquakes, which registering seismographs enable nowadays to be made continuously, gives us new information as to the rigidity of the terrestrial globe, which as previously shown, we have deduced from the tides of the crust.

When a strong earth tremor is produced at any point whatsoever of the Earth, the most distant seismographical observatories, those which for example are situated 6000 or 8000 kilometres [3600 to 4800 miles] from the initial centre of disturbance, are affected by it after several minutes, when the seismographs become agitated. If the time of the first registering of the phenomenon, propagated through the entire mass of the Earth and not simply over the surface of the crust, be compared with the actual time of its occurrence at the place of origin, it may be proved that the movement is propagated with a velocity of about 10 kilometres [6.2 miles] per second. This is a speed three hundred times greater than that of the most rapid of our express trains.

After a further few minutes, the apparatus will be again disturbed, more strongly and for a greater length of time than previously. If, as in the preceding case, we compare the times of origination and registering of the original shock we find that these other seismic waves are propagated with a velocity of 5 kilometres [3 miles] per second, viz., about half of the preceding. If we compare these results with those which the mathematical theory of elasticity gives, we find an exact agreement. In fact this theory, which is based on

experimental evidence, teaches us that if an instantaneous disturbance be produced at one point in a perfectly elastic solid, two series of waves arise in the solid, the first of which propagate themselves with a velocity double that of the second. This is precisely what the study of seismographical observations shows us, and so we have a remarkable accordance between theory and observation.

By making use of the seismographical results in the elasticity calculations it is found that the elasticity of the Earth, considered in its entirety, is of the same order of magnitude as that of steel, actually a little greater. This agrees wonderfully with the results deduced from the study of the terrestrial tides and of nutation.

We can now understand, from this knowledge of the Earth's elasticity, why observations of the propagation of seismic disturbances to the immediately neighbouring regions has never shown a velocity of more than 800 metres [½ a mile] per second. Waves are transmitted to the neighbouring points by the crust itself, while transmission to distant places takes place through the elastic medium constituted by the Earth as a whole. Thus the density of the central nucleus of our globe is confirmed; although at inconceivable temperatures this acquires, by reason of the

pressure to which it is subjected, a physical state practically equivalent to the solid state, and consequently possesses a rigidity of the same order as that of the best kinds of steel.

Earthquakes result not only in sudden shocks but also in permanent deformations of the terrestrial crust. We must seek for the origin of these, not in explosive eruptions, but in settlements, *i. e.*, in movements which affect the juxtaposed portions of the marqueterie which the terrestrial crust resembles, when such portions exhibit a certain amount of play with regard to each other. This conclusion is verified by the permanent cracks which accompany great earthquakes and which sometimes attain up to 50 or even 100 kilometres [30 to 60 miles] in length. Usually, also, one of the edges of the crevice so formed is raised with respect to the other side, which is lower. Often there is a displacement of level in the horizontal sense, and if, for example, the region affected by the earthquake is traversed by a road, this may be cut in such a way that the two pieces have no longer either the same direction or the same level. Earthquakes thus give rise to permanent deformations of the crust, deformations the origin of which is a sudden movement of the latter. The exact surveys carried

out by the government officials of the different countries have demonstrated permanent differences of level of more than 2 metres [or yards] in the regions affected by the more important earthquakes, such for example as that established by the geodetic operations carried out in Croatia after the Agram earthquake in 1885.

But in addition to these permanent deformations of sudden origin, there are also slow deformations that our Earth's crust undergoes continuously. We can only perceive these movements by an advance or recession of the seashores, which appear to encroach on the land or move seawards as the case may be. Examples of such occurrences are abundant; in the Red Sea may be seen lines of coral reef of relatively recent date, emerging above the actual sea-level, and which could only have been constructed by their microscopic builders when under a protective layer of water, which must thus have covered them not long since. In Scandinavia a kind of sea-saw movement is taking place; the bottom of the Gulf of Bothnia is rising while the southern part of the peninsula seems to be gradually sinking into the sea.

By comparing the coast reference marks traced, by Celsius, on the rocks on the shores of Sweden, in 1730, we are able to prove ground move-

ments reaching nearly 2 metres [or yards] per century, and similar facts have been verified in Norway, Finland, and Siberia. Everyone knows the classical alternation of risings and fallings exhibited by the columns of the Temple of Serapis at Pozzuoli, a movement which averages 1 millimetre [.039 inch] per year. In the Indies, subterranean forests have been discovered; in Prussia, lakes of relatively recent formation exist in depressions of the ground. Finally, in mountainous countries, a spectator placed upon a summit may see distant mountains just above a near hill in front of him; now in several cases such visibility of the distant peaks has ceased, on account of a slight upraising of the interposed hill or of a sinking of the distant peak in question. These phenomena have taken place in French Jura, in Spain, Bohemia, Switzerland, and Thuringia. The sinkings of the constituent portions of the Earth's crust are thus a general and permanent phenomenon; when they do not occur suddenly, they operate slowly, but they take place unceasingly, giving a perpetual mobility to the ground that seems to us so firm. From this, it will be recognised how great is the importance, from the point of view of the Earth's history, of those precise determinations of altitude, which are the

only means of detecting and measuring relative changes of altitude of different points on the solid surface of the terrestrial globe.

There is one further manifestation of the interior activity of the globe which may lead to terrible catastrophes, viz., the violent movements of the sea, which are wrongly called tidal waves, for they have no connection with the periodic phenomena of flux and reflux of the waters of the sea.

A tidal wave originates in a seismic disturbance occurring at a place on the bottom of the sea. Such a phenomenon may happen as a result either of a sudden upraising or a sudden lowering of the submarine surface. Let us suppose, for example, that the cause is the former; a liquid protuberance immediately forms at the upper surface of the sea over the part of the submarine surface raised. This protuberance is bordered by two hollows, the depth of which is in proportion to the height of the uplifted mass of water, and so gives rise to a wave which extends outwards over the surface of the ocean, reproducing on a vast scale the phenomenon of rings which is caused by dropping a stone into water. A wave which is called the seismic wave of translation is thus propagated over the surface of the sea. Its arrival at the coast is preceded by a lowering of the water to

the same extent, which at the moment of reaching the shore produces there a retreat of the sea. Ships are suddenly grounded on the bottom of the ports where they are at anchor. But an instant later the high wave follows this retreat, and the vessels are sometimes carried a considerable distance on to dry land by the crest of the great wave which has refloated them. Water breaks over low coasts, submerging habitations and drowning men and animals in its passage; this is what occurred at Lisbon, in 1755, when a terrible tidal wave followed a great earthquake. Thirty thousand persons were killed by these two causes combined.

Tidal waves are formidable even on coasts like those of Portugal, but are far more so in the case of low shores such as exist in the archipelagoes of Polynesia. This is especially so as they are situated in the Pacific, a region where earthquakes are numerous and therefore are more exposed to these terrible phenomena. These islands have but a very slight elevation above sea-level and when a tidal wave descends upon one it destroys everything upon it.

The velocity of propagation of these waves of seismic origin attains considerable values; they may move over the surface of the sea at the rate

of 350 to 400 nautical miles an hour. The marine mile equals 1852 metres and is the length of one minute of arc measured on a terrestrial meridian. Therefore these seismic waves of translation are propagated with the velocity of 750 to 800 kilometres [465 to 495 miles] per hour. The eruption of Krakatoa was accompanied by a violent local seismic phenomenon and this produced a gigantic wave of translation, which made itself felt two days afterwards by the tide recorder at Rochefort. In the regions of Japan or Peru earthquakes frequently accompany volcanic eruptions, and on every occasion it has been shown that the wave traverses the entire width of the Pacific in twelve hours.

Oceanographers have made a study of this propagation and found a simple law governing it. If the mean depth of the ocean at whose surface the wave is moving be multiplied by the mean intensity of gravity along the track of the wave, the square root of the product is equal to the velocity of propagation. As a consequence of this simple law we may in nearly every case deduce the mean depth of the ocean over whose surface the wave passes. For we can usually determine the velocity of propagation of an important seismic wave of translation, since the earthquake

giving rise to it occurs at a known hour, and the moment the wave reaches the opposite shore of the sea or ocean also can be precisely found by means of tide recorders. The mean intensity of gravity along the path of the wave is also known. A remarkable agreement is found between the results of direct soundings and those furnished in this manner, constituting a beautiful confirmation of the theory of the propagation of the waves.

# CHAPTER VIII

## THE MAGNETISM, ELECTRICITY, AND RADIOACTIVITY OF THE EARTH

THE preceding chapters have shown us how far the terrestrial globe resembles a living being, with its period of growth and development, its internal activity, the regular pulsation of its crust, and the convulsive shocks which agitate it at intervals. We are now to see that phenomena of circulation are produced in the terrestrial crust under the form of electric currents with associated magnetic phenomena, which are inseparable from the former. The likelihood of magnetic phenomena is obvious from what we have previously learned about the Earth's nucleus. By reason of the enormous pressures to which its various parts are subjected, it is in a condition practically equivalent to the solid state, in spite of the high temperature, and is furthermore constituted of metallic elements, among which iron predominates. It is thus not surprising that the terrestrial globe in its entirety should exhibit magnetic properties.

On the other hand, the Sun possesses a considerable electrostatic charge and therefore creates an electric field about itself. The physicist Nodon was undoubtedly the discoverer of the electric action of the solar rays; in 1885, he proved that the Sun's radiation produced a positive charge in an insulated conductor, a charge which increased with the intensity of the radiation, the phenomenon ceasing when clouds passed before the Sun. In 1905, Bernard Brunhes confirmed Nodon's results by a very beautiful series of experiments, and Nodon himself, at the Pic du Midi in 1907, clearly demonstrated the solar electrical action. Our Sun is therefore charged with electricity. This charge doubtless surpasses in magnitude any imaginable one; Arrhenius's calculations show that it is always as great as 250 thousand million coulombs.[1] It produces an electrostatic field.

The charge, turning rapidly around the Sun's axis of rotation, must give rise to a magnetic field, this latter being a consequence of the motion of a charge, as was discovered by Rowland. This phenomenon was disputed for a long time, but the experiments of the Roumanian physicist

[1] A coulomb "is the quantity due to the passage of a current of 1 ampere for 1 second, or of ½ ampere for 2 seconds, and so on" (Ganot's *Physics*).—*Ed.*

Vasilesco-Karpen have definitely verified its existence and measured it quantitatively. The intensity of the field so created is doubtless considerable in the neighbourhood of the solar surface but certainly feeble at a distance such as that of the Earth from the Sun, for the law of decrease of magnetic action is that it is inversely as the cube of the distance. Nevertheless, even if feeble, the field undoubtedly exists, and the conducting nucleus of the Earth moves through it with great velocity like the armature coils of a dynamo in the field of its field-magnets. There must, thus, be produced "Foucault's currents" which flow through the terrestrial mass.

This is not all, however; the positively electrified surface of the Sun sends into space small negatively charged particles; as we have previously seen, this repulsive effect being superior to the attractive force in the case of very small particles, because the pressure of radiation is relatively greater upon them. Many of these minute fragments reach the Earth's atmosphere. The effect of ultra-violet light, as the work of Lenard has shown, is to discharge these particles, and it is their negative charge which escapes in the form of what are called electrons in the language of modern physics. These electrons are excessively small,

and some idea of them may be obtained from the fact that a thousand of them weigh almost as much as one atom of hydrogen, while one gram [15.4 gr.] of hydrogen contains a number of atoms represented by the figure 1 followed by twenty-four zeros.

By the well-known demonstration of iron filings arranging themselves along the magnetic lines of force, we know that these lines of force converge to the poles of a magnet (Figs. 23 and 24). Now, the rays of the solar corona have a deflection towards the equator from the poles similar to the lines of the magnetic figures. We may therefore suppose that the Sun behaves like a great magnet, the magnetic poles of which practically coincide with the geometrical poles.

Electrified particles shot forth from the Sun may reach the Earth, and, in the course of the present chapter, we shall see beautiful experimental verifications of this theoretical conception. These particles convey their charges, the influence of which is felt in the atmosphere and at the surface of the ground. The ions of the upper atmosphere partake of the Earth's movement; they have been repelled by the Earth, which is similarly electrified, and remain in the higher layers of our atmosphere, where they produce electrical

phenomena which have a powerful generative or modifying action on the terrestrial magnetism.

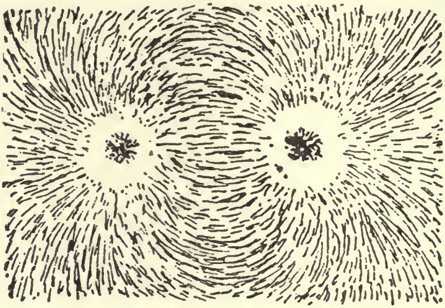


FIG. 23.—Magnetic Lines of Force (Two Poles of Opposite Sign), after Prof. Stanoïévitch.

To recapitulate, the Earth moves in an electric and magnetic field due to the Sun, and receives

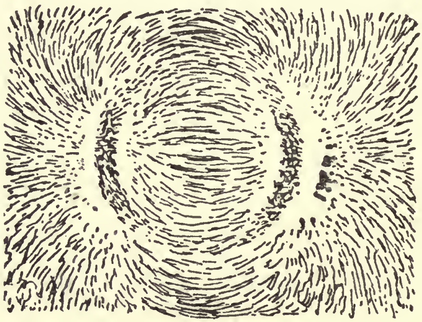


FIG. 24.—Magnetic Lines of Force (the Two Poles of a Circular Magnet after Prof. Stanoïévitch.

from the Sun particles which bring charges to its surface. Any change in the intensity of the solar

radiation will modify the intensity of the observed effects; also any change in the velocity of displacement of the Earth in this field will cause the indirect effects to vary. Now, Kepler's law tells us that such modifications of velocity do occur, and we may therefore expect periodical variations of electric and magnetic phenomena. Such being the theoretical considerations, we shall now examine the results of actual observations.

Terrestrial magnetism, with which we shall commence, shows itself in a simple way by the directive effect which the Earth has on a magnetised needle freely suspended at its centre of gravity. This elementary experiment, more or less modified, is the basis of all our study of the manifestations of the Earth's magnetism.

The vertical plane which contains the needle is called the magnetic meridian. It points nearly towards the north pole of the Earth, but in general does not coincide with the geographical meridian of the place, the angle between the two being called the declination. The angle made with the horizontal by the needle is known as the inclination, and the intensity of the horizontal component of the force directing the needle, which is an important quantity, is often called the horizontal intensity.

If a magnetic needle be suspended and means are furnished for the measurement of its direction with all possible precision, it may be proved experimentally that, in any one place, the magnetic elements vary during each day. These variations recur regularly every day in the year, and their mean values also vary according to the season. As regards the declination, which is actually 10° to the west at Paris (1912), this quantity passes daily through a maximum and minimum value, but the actual degree of variation is slight, attaining only a few minutes of arc. The inclination and the horizontal intensity undergo analogous variations, but these differ in sign in the respective hemispheres. The variations are greater in warm weather than in cold weather.

The declination shows annual periodical variations such as the theory indicates; every year there is a maximum and a minimum, the changes of sign, that is to say the passages through the mean value, taking place about the time of the equinoxes. These epochs also determine the change of sign of the variations of the inclination and the horizontal intensity.

No relation between the lunar period and the variation of the magnetic elements has yet been established with certainty. It is the contrary

with regard to the solar spots and we here find one of the most beautiful confirmations of the theoretical views which we have enunciated at the beginning of this chapter. The years of maximum solar spots are those in which the variation of the declination and that of the horizontal intensity also attain their maxima, and the curves which represent these three phenomena more or less coincide with one another.

Thus, at any one place, the declination, in common with the other magnetic elements, undergoes variations of daily and annual periodicity, and also one of 11½ years' period, and these all correspond to the known periods of the variations of the effects resulting from the solar activity, whether on account of the varying amounts of heat received by the Earth, or by reason of the variation in the distance between the two bodies, or finally because of the change in the radiation emitted by the Sun.

But this is not all; if the declination be carefully observed, and if its mean value be taken for each year, it may be proved that it varies showly from one year to another and that this secular variation appears to be also periodic. At Paris, for example, observations of the declination have been made since the year 1540. The phenomenon itself was

discovered by Christopher Columbus, in 1492, at the time of his voyage resulting in the discovery of America. Now, in 1540, the declination at Paris was to the east, that is to say the magnetised needle pointed to the eastward of the geographical north (Fig. 25); its value subsequently increased and passed through a maximum value a little before the year 1600. Then it began to decrease and reached zero in 1660, in which year compasses indicated the true north in the French capital. After 1660, the declination changed sign and became westwards, increasing in value each year. At the beginning of the nineteenth century, it attained a maximum of about 24° since when, though remaining westwards, it has continually diminished. Actually it is about 10° to the west and is thus approaching the zero value again, when it will change sign and pass to the east, where it was before 1660.

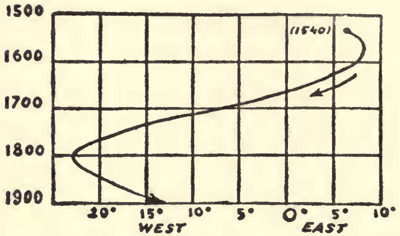



Fig. 25.—Secular Variations of the Declination at Paris.

As regards the inclination, the precise results of direct observations are less decisive, and its importance, for sailors and travellers, is much less

than that of the declination, which gives them a fixed direction when the stars are hidden by cloud. But, in the course of recent years, Giuseppe Folgheraiter has thrown a great light on the matter by some very original work.

Potter's clay is magnetic; a vase moulded from such clay becomes therefore magnetised by induction under the influence of the terrestrial field, that is to say it exhibits two poles so placed that the line which would join them is parallel to the direction of the dip needle. Thus the vase behaves just as a piece of soft iron would. But, if while thus subjected to the action of the Earth's magnetic field, the clay vessel is placed in an oven and baked, its magnetisation will become permanent and the two poles, situated on a line parallel to the direction of the dip needle, will remain permanently. If, therefore, we knew in what way the vase was oriented in the oven with respect to the geographical north we could deduce, by investigation, its permanent magnetism, both the direction of the magnetic meridian and the value of the inclination at the time when it was baked.

The researches of Folgheraiter were carried out on Etruscan vases, the antiquity of which is considerable. These vases, having the forms of

surfaces of revolution, give no exterior indication by which we can arrive at their orientation in the oven at the time of their manufacture; they cannot thus furnish us with any information as to the declination. But as regards the inclination, which is the angle made by the magnetic needle with the horizontal, they give us a sufficiently exact value, for they were always placed on a horizontal plane in the baking oven and, whatever subsequent positions they were placed in, the angle made by their poles with the horizon can be determined by again replacing them in a horizontal position.

A very remarkable result was deduced and it was at first very much disputed, viz., that the magnetic inclination must have been zero, in Central Italy, towards the middle of the sixth century B.C., and that in the preceding years, that is to say in the course of the seventh century B.C., several specimens of the art of which remain to us, the north pole of the magnetic needle was inclined above the horizontal instead of below it as at the present time.

Bernard Brunhes, in 1906, was enabled to confirm these conclusions of Folgheraiter by means of investigations he carried out on the permanent magnetisation of the lavas of the Puy-de-Dôme. His work dealt with the metamorphic clay of the

lava of Pontfarein, in Cantal; in contact with the burning lava this clay is baked *in situ* as if it had been in a pottery oven. Brunhes has deduced clear indications of a change of sign of the inclination having occurred in these regions at an epoch not very different from that which Folgheraiter indicated.

Brunhes has, however, done yet more. He has made a study of the pavement of the Temple of Mercury erected on the summit of the Puy-de-Dôme and has justified the principle of the work of the Italian scientist. The paving stones which form the floor of the temple are constituted of volcanic rocks and each one has retained a permanent magnetisation. The declination deduced varies from one stone to another, as would be expected, since they are oriented in different ways, but the inclination is the same for all; the elements of their magnetisation, which date from the time of their cutting, have therefore not been affected by the subsequent variations of the terrestrial magnetism. Consequently the conclusions of Folgheraiter on the ancient values of the inclination, deduced from the study of the Etruscan vases, are perfectly legitimate.

Thus the magnetic elements not only vary in the course of each day, each year, and each eleven-

year solar period, but also suffer slow variations in the course of successive centuries. Here we again realise that there is a perpetual evolution in those forces, the play of which constitutes the life of our Earth. We shall now see that these variations with time are not the only ones, but that there are also variations according to position on the Earth's surface.

A magnetised steel needle freely suspended about its centre of gravity takes up a position inclined to the horizontal. By applying a light counterpoise to the higher end, we are able to force it into the horizontal position and we may then prove that it will always direct itself towards a point on the horizon called the magnetic north, being free to move in the horizontal plane in which it is constrained to remain.

If we move over the Earth's surface, walking always in the direction of a horizontal magnetised needle, that is, a declination needle, we shall go towards this special north, and our journey will be, not along a terrestrial meridian, but over a curved line which is called a magnetic meridian. All such magnetic meridians converge towards a point situated in Northern Canada, to which the name of the North Magnetic Pole has been given. In the southern hemisphere, there is a

South Magnetic Pole, situated in Victoria Land, part of the Antarctic continent not far from the volcanic mountains Erebus and Terror. The North Magnetic Pole has been several times reached by explorers, the latest being the Danish explorer Roald Amundsen some years ago; as regards the South Magnetic Pole, Sir Ernest Shackleton determined its position in 1910. It should be noted that at either of these poles a magnetised declination needle will lie equally in any direction and not only in one fixed one, whereas the inclination needle is vertical. It is this latter which enables us to determine the situation of the magnetic pole.

The magnetic poles are not fixed at the Earth's surface. They are distant from the geographical poles, but the North Magnetic Pole, although incessantly moving, never wanders far from latitude 69° north, while the mean latitude of the South Magnetic Pole is 75°. Between 1770 and 1888 the North Magnetic Pole moved from latitude 66° to latitude 71°; it has reached a point more than 600 kilometres [372 miles] nearer the terrestrial pole than at the earlier date. It now appears to be retreating again. This non-fixity of the magnetic poles, the incessant fluctuation of their position, corresponds to the secular varia-

tion of the elements of terrestrial magnetism, and one of the phenomena is a direct consequence of the other.

In order to go from one point on the Earth to the magnetic pole we have only to follow a route always tangential to the direction of the inclination needle. For every place on the Earth the value of the declination may be measured, that is to say the angle between the directions of the needle and the geographical meridian may be found. By such means it can be shown that the declination varies from one point to another of the globe. It is a matter of the greatest importance, for sailors and travellers, to know these variations for the different parts of the Earth, since when they are unable to observe the stars in order to deduce the position they are in at any time they can only direct themselves by means of the magnetic needle. Consequently it is essential to know the difference between the magnetic north and the true north at a given place, and how this difference varies from point to point of the terrestrial surface. Magnetic maps of the Earth have been drawn up by tracing on a planisphere lines passing through points on the Earth's surface where the declination has the same value; these lines are called isogonic lines.

It is obvious that all the isogonic lines must pass through the magnetic poles. They also pass through the geographical poles, since the declination is the angle between the magnetic meridian and the geographical meridian. As all

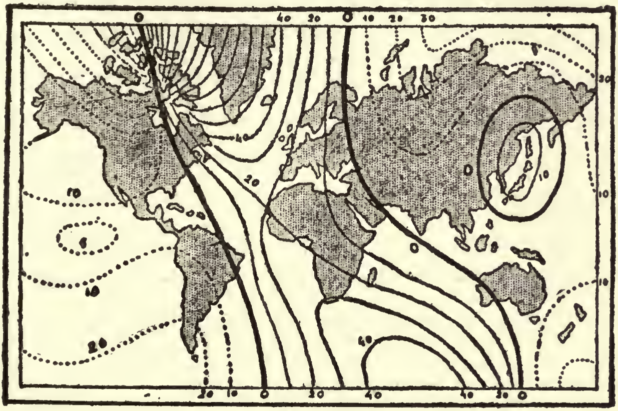


FIG. 26.—Chart of Isogonic Lines or Lines of Equal Magnetic Declination.

geographical meridians pass through the poles of the Earth the declination there can have any value, so that the isogonic lines must all meet together there. Fig. 26 gives an idea of such a map. Similar curves have been drawn for the inclination and the horizontal intensity, but the importance of the declination for navigation and land journeys makes the isogonic maps of more immediate interest.

There are certain peculiarities which strike one at once upon this map, for example, there are three lines of zero declination, drawn thicker than the rest.

Between the two chief thicker lines passing through points on the Earth where the declination is zero are found regions where it is west; outside them it is east. Nevertheless there are two portions of the Earth's surface characterised by singularities. There is a closed curve on Eastern Siberia, along which the declination is zero, and in its interior the declination again becomes west. Also in the Eastern Pacific there is another closed curve corresponding to a minimum declination. It will be seen from these remarks how curious the distribution of terrestrial magnetism is.

As the magnetic elements vary with time and also according to the region of the Earth considered, it is obvious that magnetic maps should be frequently remade to correspond with the new values of the elements, so that travellers should have correct data and not erroneous ones which might lead them wrongly, and even into danger.

The variations of the magnetic elements of which we have spoken up to the present have been the slow and continuous ones; there are others

of a sudden character which constitute magnetic storms and perturbations.

When magnetic instruments of great precision are installed in an observatory, enabling us to indicate, and preserve by photographic registration, the least variation in terrestrial magnetism, we ordinarily observe the periodic variations that have been described above. But on certain days the needles are agitated; they tremble and exhibit quite erratic movements, their oscillations obeying no regular law. Often in such cases these irregularities and agitations of the magnetic needle are great enough to be observed in ordinary compasses. Such a phenomenon is called a perturbation or magnetic storm.

A magnetic storm always makes itself felt over a considerable portion of the Earth's surface, and very frequently its occurrence coincides with polar auroræ and with important seismic phenomena. We have seen that it is possible to conceive how the movements of the internal nucleus may affect the magnetism and produce disturbance of the crust, so that it is not surprising that these phenomena exhibit a certain degree of coincidence. We shall see later on why polar auroræ often manifest themselves at the same time as magnetic storms. It is an incontestable fact, the result

of actual observation and not only of theory, that the forms of the curves representing respectively the periodicities of the solar spots, the auroræ boreales, and magnetic storms are identical; the three curves have exactly the same aspect and the same irregularities.

Independent of the general variations which the Earth's magnetic elements undergo as we pass from one point of the surface to another, local anomalies may be observed exactly analogous to the case of the value of the intensity of gravity, where we observe local irregularities arising from particular local effects at the given point in question. The crust being of varying thickness, the surface is consequently unequally distant in different parts from the central nucleus containing the metallic elements to which the earth's magnetism is due. Furthermore, as the crust itself may contain more or less magnetic mineral matter, we may readily understand how purely local variations may arise from both these causes, viz., an exceptional thickness or thinness of the crust at the place under consideration and its geological nature.

This general explanation, while it is doubtless sufficient in many cases, is, however, far from satisfactory in others. Thus, in the region of Paris,

there exists a very marked local anomaly; the isogonic lines are folded on themselves in the form of an S with very serrated bends. Now it is not possible to find a magnetic cause of this anomaly in the geology of the Parisian region; the strata are, in fact, chalk. The question arises whether the cause of the anomaly is to be sought for in the deeper strata. The S-shaped curve formed by the isogonic lines seems to be the continuation of a great fault in the district of Bray, and possibly this fault, by reason of the resulting geological modification, affects the circulation of the electric currents which, as we shall shortly see, incessantly traverse the terrestrial crust. Another suggestion is that as the Tertiary Parisian basin was in some measure a marine formation, the ocean which formerly existed there corresponded to a thinner crust, according to the theory of Lippmann, and consequently the magnetic interior of the Earth is relatively near the surface of the ground in that region. The matter has not yet been fully elucidated.

Magnetic phenomena are not the only ones that indicate the Sun's influence upon the Earth; there are electric phenomena which manifest themselves in various ways around us; the first and the most important, from a practical point of view, is the

existence of earth currents. In the early days of the electric telegraph the physicist Matteucci showed that, at times, the telegraph lines indicated grave disturbances, and he remarked and called attention to the coincidence of these perturbations with magnetic storms and the appearance of polar auroræ.

At the present time, the phenomenon is better known, and telegraph lines are the best possible instruments for its study. It consists of the passage of currents quite different to those which circulate normally in the wires. These, being superimposed on the currents transmitting the messages, confuse the latter and produce signals which are unconnected with those despatched along the wires.

These earth currents make the bells ring and sometimes even cause a spark to pass between different parts of the receiving apparatus. The electromotive force of these currents is sometimes nearly 1000 volts, the lines they traverse being several hundred kilometres [or miles] in length. By utilising for their study the telegraphic line which connects Clermont-Ferrand with the summit of the Puy-de-Dôme, Bernard Brunhes has clearly proved the influence of the inclination of the line on the degree of their manifestations, which

seem to have little connection with atmospheric phenomena, but appear on the contrary to correspond closely with magnetic phenomena. Like the latter, the earth currents follow a regular periodicity and thus show recurrent variations, but the chief perturbations have an accidental character, and almost always coincide with the appearance of polar auroræ, also with magnetic storms and with important seismic disturbances. At the beginning of November, 1903, telegraphic perturbation of the kind caused by earth currents took place, producing an almost complete interruption for two days of the service in Western Europe. This very intense manifestation of the special activity of the earth currents coincided exactly with an aurora borealis, with a magnetic storm of exceptional intensity, and with an earthquake which destroyed the town of Turchiz in Persia on November 1st. Furthermore, it is remarkable that, at the same time, a spot of extraordinary dimensions made its appearance on the Sun's surface. In order to render complete our account of terrestrial electric currents, it should be added that there are also currents between the ground and the atmosphere; a positive current appears to flow upwards from places of mean latitude and to be transmitted by the upper

atmospheric layers, returning to the ground in the neighbourhood of the equatorial regions, the circuit being completed by the current traversing the ground from south to north. So there is an effect analogous to the true earth currents, and one which in certain cases is probably superimposed on them.

Thus, we have the fact that these electric manifestations, the earth currents, bear some direct relation to the solar activity, and, consequently, with all the phenomena that depend on the latter, which we have noted at the beginning of this chapter. This relation is another confirmation of those theoretical conceptions which trace to the solar energy and its fluctuations all the very varied manifestations of energy observable at the Earth's surface. But it is not only the action of the solar radiation that produces electric phenomena at the surface of our globe; another cause is to be sought in the dust particles repelled from the Sun, if sufficiently small, by the pressure of its radiation, and consequently driven forth into space. These particles give rise to another class of electric phenomena which occur in the terrestrial atmosphere.

The Sun, being in a magnetic condition, presents two magnetic poles, just as the Earth itself does.

The Solar Corona, according to the beautiful theory of Arrhenius, is composed of very minute particles which the pressure of radiation has driven far away from the Sun's surface. The coronal streamers, formed by these particles which come from the region of the Sun near the poles, are deflected under the influence of the magnetic lines of force emanating from these poles, which act upon the negatively electrified particles. On a large scale, it is exactly the same as the elementary physical experiment of the magnetic figures obtained with iron filings, demonstrating both the existence of the lines of force and the direction of the field. Under the repulsive action of the pressure of the Sun's radiation part of this solar dust arrives in the neighbourhood of the Earth. As the latter is magnetic and has two poles, it exerts an influence upon the particles. Consequently these become grouped into two streams which are directed towards the magnetic poles of the Earth, and, as in all probability the magnetic poles do not crop out at the surface of the ground, but are situated at some depth in the Earth's interior, these attracted streams are simply drawn towards a region of roughly circular form surrounding the terrestrial magnetic poles. When the multitude of arriving particles is more abundant than usual,

owing to exceptional solar activity at the time, their electrification is bound to affect the Earth's magnetism.

When the dust particles enter the atmosphere, and so meet the molecules of air, they produce a phosphorescent glow exactly as if this air was subjected to the action of electric radiation arising from a piece of some radioactive substance. In other words, the negatively electrified particles driven from the Sun are discharged on entering the upper regions of the Earth's atmosphere and emit cathode rays, to which the polar auroræ are due. Professor Birkeland has attempted an experimental study of the particular circumstances of the origin of the aurora, by means of laboratory researches. He took a sphere of magnetised steel, representing the Earth, covered with a fluorescent coating. He then exposed the sphere to the action of cathode rays, the point of contact of which with the sphere was shown by the illumination of the fluorescent coating produced. Thus, he artificially reproduced luminous phenomena resembling polar auroræ, and as he used the cathode rays, which are now considered to consist of small negatively charged particles moving with considerable velocity, just like the solar dust above described, the experiment affords a beautiful

confirmation of the theory of auroræ that has just been briefly given.

Another confirmation has been furnished by the remarkable observations of the Italian astronomer Ricco. If the theory is exact and if auroræ, and the electric phenomena of which the Earth is the seat, have their origin in the dust particles expelled from the Sun's surface, we should expect more important manifestations at the epochs of greatest eruptive solar activity. These epochs are those at which the solar faculæ are most developed, at which periods the sun-spots also are largest and most frequent. In a word, the maxima and minima of auroræ and of magnetic perturbations should coincide with those of the Sun's activity, and observation has already shown that such is the case. Now, if the cause of auroræ is to be found in the contact of solar dust with the Earth's atmosphere, this dust, which is material substance, cannot be transmitted through space with an infinite velocity, but on the contrary must occupy a certain time in reaching us from the Sun.

It is actually possible to calculate this velocity. Let us consider a very small non-transparent particle .00016 millimetre [1 mm. = .03937 in.] in diameter, a size which corresponds to the maximum value of the pressure of radiation and consequently

to the greatest velocity of propulsion, and let this particle have unit density, the same as that of water. The particle will be subjected to the action of the solar gravity, which attracts it towards the Sun, and to that of the repulsive radiation pressure, which is two and a half times greater than the former. A mean velocity of 740 kilometres [450 miles] per second is thus arrived at by calculation, and this implies that the particle takes fifty-six hours to pass over the distance separating the Sun from the Earth. It should be remarked that we have assumed the density of the dust particles to be equal to that of water, but they have in all probability a less density than this, since they are probably formed of hydrocarbons containing hydrogen and helium in solution. If the particles considered have a density equal to two thirds that of water, the calculation gives the result that under the resultant repulsion force the particles would reach the Earth from the Sun in forty-five hours.

Now Ricco has found precisely an interval of 45½ hours between the passage of a sun-spot over the solar meridian and the maximum amplitude of the corresponding magnetic perturbation, this result being based on half a score of clearly observed cases; in another series he arrived at an interval

of 42½ hours. This constitutes a remarkable concordance between calculation and observation, and justifies a feeling of pride that Man is able so to overleap the apparent limitations of his environment and attain to knowledge from which at first sight he would seem for ever debarred. The explanation of the mysterious auroræ is thus simple; they surround the pole of the line of fall of the dust particles which produce them and so appear to shine to the north of this line for places which are exterior to it, and towards the south for those which are contained within it. Physicists call this line the neutral line.

The study of the presence of the solar dust in the Earth's atmosphere enables us to understand yet another thing. The negatively charged particles driven, as we have already seen, from the Sun by the pressure of radiation, meet our atmosphere and discharge themselves to earth, producing auroræ. This discharge of negative electricity communicates to the Earth's surface, and maintains an electrostatic negative charge which constitutes what is known as atmospheric electricity. A study of this phenomenon has shown that the electrical potential increases in proportion as the point of observation is higher above the ground; in the neighbourhood of the

ground the increase of potential with height is, on the average, 150 volts per metre [39.37 in.]. The Earth's charge augments when the solar spots increase.

We cannot, here, enter into a detailed description of the effects of atmospheric electricity; lightning, thunder, electrification by induction and the effects of thunder-storms, are all clearly described in works on elementary physics and in popular books. What we have to remark here is that there appears to be a direct bond between solar activity, the cause of the Earth's life, and storms, which are one of the most striking manifestations of terrestrial activity. The high clouds which float in the atmosphere, the cirri, are formed in great abundance as a consequence of the production of auroræ. We know in fact that when the air is charged with water vapour and when also a strong ionisation has been produced under the influence of the cathode rays, condensation is facilitated, or, in other words, circumstances are favourable to the formation of clouds, the ions having the property of condensing vapours. Abundance of cirri should thus accompany the maxima of solar spots. Observations during fifty years permit us to state that there is an agreement between the maxima of the number of cirri and

the maxima of the number of sun-spots, the periods of both phenomena being eleven years.

Cirri may also be electrified by the action of ultra-violet rays. These rays have the property of rendering gases conductors of electricity, that is to say, of ionising them. Furthermore they discharge the negative electrification of any body they fall on, while not affecting the positive charge. Cirri, which are formed of fine needles of ice, often pass above clouds that have been inductively electrified by the proximity to the ground; in this case they are in turn subjected to the inductive influence of these clouds and their component needles are charged, negatively at one extremity, positively at the other. In these conditions if a beam of cathode rays should happen to strike them their negative charge would be dissipated, and they would remain positively charged. Here again, consequently, we trace to the Sun an electrical atmospheric phenomenon.

The importance of these electro-atmospheric phenomena is extremely great, especially as regards the Earth's animal and vegetable life, for they determine the combination of the nitrogen of the air with oxygen and hydrogen and accordingly give rise to nitrates, nitrites, and ammoniacal compounds, the great importance of which is now

understood by agriculturists. These compounds of nitrogen are carried down to the soil by the action of rain, and in this way more than 400 million tons are brought down yearly.

There is, finally, another electrical property of the Earth, viz.: its radioactivity. At the commencement of the history of radioactive phenomena, which were discovered by Becquerel, in 1896, and of which radium, subsequently discovered by Mme. Curie, will facilitate the study, it was believed that only minerals which had produced radioactive bodies, for example, the pitchblende from which uranium is extracted, possessed these remarkable properties. We now know, however, that the phenomenon is general, and that all bodies are more or less radioactive. The terrestrial crust is the seat of a radioactivity which may be demonstrated by pushing a tube into the ground for a depth of one metre [or yard] and breathing the air found there; this air is always more or less charged with emanations. It follows that the air in caves or caverns is especially so charged. All mineral waters are radioactive, as Professor Moureu has discovered; they contain these rare gases of which one, helium, has been obtained by Sir W. Ramsay as a product of the transformation of radium emanation. As this

emanation is very rapidly dissipated, this explains why the greater number of these waters are only efficacious, from the therapeutical point of view, when drunk directly from the source, before the gases have had time to dissipate, while when conveyed to a distance they lose all the gases which constitute the chief cause of their curative power and become merely simple saline solutions. Professor Moureu has even shown that, excluding helium which is one of the products of radioactive emanations, there is a constant mutual ratio between the amounts of the rare gases argon, krypton, xenon, neon found both in mineral springs and in natural gaseous mixtures such as mine emanations.

This is readily understandable; at the origin of the Earth's formation by the process of condensation, these gases did not combine with any other of the elements that were successively formed, owing to the chemical inertia of the former, inhibiting the production of compounds. They therefore remained in the free state while the other elements formed combinations among themselves; consequently they have persisted unchanged through, and unaffected by, all the cataclysms and convulsions which have marked the successive states in the Earth's history.

The atmosphere in contact with radioactive soil is itself radioactive. Physicists always find there traces, of course infinitesimal, of the emanation, and freshly fallen rain or snow invariably shows signs of radioactivity; it is the same with the water of the sea. Concordant experiments have demonstrated that the activity of a gram [15.4 gr.] of radium is halved in about 2000 years; throughout that time it continues to emit 120 calories[1] per hour, say in round numbers, one million calories annually. If, therefore, the terrestrial globe contains a quantity of this substance in its central core it would possess a considerable reserve of internal heat. How can radium thus give out heat-energy for so long a time? Does it absorb some kind of radiation from space which it is able to transform into heat by unknown means?

The radiation of radioactive bodies comprises three species of rays: (1) the $\alpha$-rays, composed of positively charged particles, travel approximately 20,000 kilometres [12,400 miles] per second; these particles are atoms of helium; (2) the $\beta$-rays, which are negative electrons whose mass is $\frac{1}{1700}$ part of that of an atom of hydrogen, and which

[1] A calorie is the amount of heat required to raise 1 gram 15.433 gr.] of water 1° Centigrade [=1.8° F.].—*Ed.*

move with the velocity of light[1]; (3) the $\gamma$-rays, analogous to the X-rays.

Helium is always found in radioactive minerals and it is derived from radium emanation. Helium, therefore, seems to be an ultimate element; it occurs as the final product of the disintegration of other atoms; it represents in fact a starting point for the integration of the more complex atoms.

Radioactive substances—uranium, actinium, radium—set free helium. Sir William Ramsay has proved this fact in regard to radium; other experiments have enabled him to ascertain that copper is transformed into potassium, sodium, and lithium and also that lead, thorium, titanium, and silicon become transmuted into carbon under the influence of the energy set free by the radium emanation. If these experiments be confirmed, this result is of the most supreme importance as regards the theory of matter. In any case, potassium, sodium, and rubidium are feebly, but distinctly, radioactive. It thus appears that radioactivity is a general property of matter.

Heavy atoms become transformed into simpler ones, losing energy in the process. This degrada-

[1] Velocity of light = 300,000 kilometres [186,000 miles] per second.—*Ed.*

tion is spontaneous, and it is only when it is occurring with a slowness that renders it quite imperceptible in the duration of our existence and experiments that we consider such matter as stable.

But now arises the question as to the origin of the heavy atoms, for example those of thorium or uranium. These by breaking up and transformation can give birth to those of lesser atomic weight but cannot themselves arise from a previous degradation. It is therefore natural to suppose that they arise from an inverse process of integration of matter, starting from simple atoms such as helium, under the influence of considerable energy.

We are here led back, in this consideration of the origin of radioactivity in the Earth's crust, to the important problem of the age of our globe. We have seen in a preceding chapter that the period that has elapsed since the formation of the solid crust lies between 1000 and 2000 million years. If we try to formulate the time that has passed away since the Earth became an independent body, after its detachment from the nucleus of the solar nebula, we must reckon at least a million million years.

If the Earth had been entirely formed of uranium, a million million years would have been a more than

sufficient time for the whole of it to be transformed. Now uranium is actually found in the Earth's crust, whence we must conclude that this radioactive substance is formed in the mass of our globe.

If the Earth contained $\frac{1}{5,000,000,000}$ of a gram of radium per cubic centimetre, this would suffice to prevent its cooling; we know at the present time sufficient of the constants of radioactive material to make such a calculation. Now observation shows that the radioactive material in the terrestrial crust is, on the average, twenty times greater than this. Our Earth should therefore be getting hotter and the deduced duration of the geological periods would be increased beyond all probable limit. Consequently we must assume, as the English scientists have done, that the whole quantity of radioactive material present in the Earth is contained in a very thin layer of the Earth's crust situated in the immediate neighbourhood of its exterior surface. The thickness is probably only a very few kilometres [or miles]. Thus we are brought to a difficulty. Either the interior of the globe contains neither uranium nor thorium or else the heavy atoms of these substances are formed there by the integration of matter under the influence of the colossal pressures which obtain in the mass of the central nucleus.

Moreover, Arrhenius has considered the possibility of formation, in the central parts of bodies whose inner regions remain heated, of endothermic compounds, locking up an immense quantity of energy, truly explosive bodies in comparison with which dynamite and the picrates would be mere playthings!

In discussing the origin of radioactive substances we have thus found a remarkable consequence, viz., the necessity of supposing that the evolution of matter constitutes a cycle. There is atomic decomposition or disintegration on the one hand, and on the other there is certainly a compensating integration, which assures the permanent coexistence of all kinds of matter.

All the facts of which we have taken note in the course of this chapter point to one thing, viz., that the Earth possesses a magnetic state.

What is this state? How are the elements, to which the magnetic action of the Earth is due, distributed under the surface on which we live? How are they arranged in such a way as to show the influences of solar radiation? These are questions to which the science of Physics can at present give no definite answers.

Fortunately, however, in the absence of answers which could be furnished by some great theoretical

conception that has yet to be attained, an English scientist, M. H. Wilde, of Manchester, an ingenious and expert experimenter, to whom we are indebted for the first self-exciting dynamo, has constructed a wonderful apparatus which, with an almost marvellous exactness, reproduces not only the actual distribution of magnetism on the Earth's surface but even the secular variations of this distribution in the course of centuries. This instrument has been named by its inventor, the magnetarium. Wilde was led to this conception by his quite original cosmogonical theory, and the accuracy of the magnetic results, therefore, also emphasises the value of this theory. Since, for the first time, all the peculiarities of such a complex phenomenon as that of the distribution of terrestrial magnetism and its secular variations have been artificially reproduced in the laboratory, the theoretical ideas which led to such an achievement cannot be valueless and merit the fullest attention of those scientists, who by the aid of mathematical analyses make it their province to construct theories concerning the origin and functions of worlds.

We have seen in studying the birth of the Earth that the spheroidal agglomeration of incandescent material, which at a later period constituted our

planet, gradually cooled in such a way as to become surrounded by a superficial solidified layer. On the other hand, we also know that the Earth while traversing its orbit remains inclined to the plane of the orbit, the angle between the planes of the orbit and the Earth's equator being $23\frac{1}{2}°$. Wilde holds that it was not always so and that at a certain time, extremely long ago since we are considering the incandescent phase previous to the formation of the solid crust, the Earth rotated about an axis perpendicular to the plane of the ecliptic. In these circumstances the magnetic axis of the system of electric currents arising from the solar energy would be parallel to the polar axis about which the incandescent spheroidal Earth rotated. At a later period, the superficial solidification occurred, covering the mass with a rocky crust. Wilde believes that at that time the axis of rotation about which the crust turned was inclined to the ecliptic as at present, while the central nucleus continued turning about the axis of its original rotatory movement. Thus, according to the English physicist, in place of a single permanent axis, the Earth has possessed two from the time of the formation of its crust: first, the actual axis, serving as axis only for the solid envelope; secondly, the primitive axis upon which

turns the igneous mass that constitutes the central nucleus of the globe. Furthermore, Wilde has arrived at the conclusion that this internal mass rotates about the primitive axis with a smaller angular velocity than that of the crust turning about the inclined axis.

Another point of the theory is that the superficial layers became magnetic as they cooled, the magnetisation taken as a whole being parallel to the inclined axis, so long as, at the time of its solidification, the exterior surface of the crust remained almost level. But from the time when the crust became subject to foldings and contractions, its resulting deformations produced a magnetisation of very great complexity.

To summarise, Wilde holds that the terrestrial magnetism is the resultant of two component elements, one connected with the actual constitution of the Earth's solid envelope, the other due to interior currents having as axis of symmetry a line inclined to the axis of rotation of the crust, slowly describing a cone around the latter, on account of the inequality of the velocities of rotation of nucleus and crust.

In order to arrive at a material representation of this complex phenomenon the English physicist took a sphere like those which form terrestrial

globes. This globe was mounted, as are the greater number of those used for teaching purposes, in such a way that it rotated about an axis, the two extremities of which were supported by a copper semicircular arc, forming a semi-meridian. This arc is itself capable of sliding in its own support in such a way that any point whatever of the Earth's surface may be brought to have the same horizon and the same zenith as the place of the experiment. A rigid arm, fixed to the support of the entire apparatus, enables either a small inclination needle, or a small declination needle to be placed above the point so chosen; consequently the elements of the artificial magnetism given to this magnetic globe may be experimentally measured.

In order to give his globe magnetic properties Wilde supplied it with a series of insulated wires wound according to the parallels of latitude in such a way as to constitute a sort of spherical bobbin. It follows from the laws of electromagnetism that in this case the system behaves like a sphere magnetised in a direction parallel to its axis of rotation.

This first globe contains a second one turning about a hollow axis enclosing the axis of the outer globe. The inner globe is also covered with wire

so as to resemble a spherical bobbin, but it is not wound according to the parallels of latitude; it is so wound that the poles of the spirals are the two extremities of a diameter making an angle of 18° with the axis of rotation, viz., the difference in latitude between the North Geographical and North Magnetic Poles of the Earth. A mechanism with a differential train of wheels enables the two globes to be made to turn simultaneously in such a way that the interior globe is subjected to an angular retardation of 12° in each turn relatively to the outer globe. In these circumstances it may be shown that the system is equivalent to a magnet, the line of whose poles is inclined to the Earth's axis at an angle less than 18° and which rotates continuously about that axis, the two bobbins being traversed by suitable currents supplied to them. Determinations of the declination and inclination for different places on the globe's surface were made with the above arrangement by the little test needles, but the result did not come up to expectation.

The idea then occurred to Wilde of altering the inclination of the magnetic axis of the interior globe so as to make an angle of 23½°, instead of 18°, with that of the exterior globe. In other words the two axes made an angle with each other

equal to that between the planes of the terrestrial equator and the ecliptic; consequently at certain periods of the movement the magnetic axis of the interior globe became perpendicular to the plane of the terrestrial orbit. The instrument so arranged showed approximately the successive values of the magnetic elements observed at London. One complete turn of the exterior globe corresponded to an angular displacement of 12° with reference to the interior globe, which corresponds to an interval of time of thirty-two years. We, therefore, draw the conclusion that the general period of the secular variation is about 960 years.

The results, however, although giving fairly exact values for the magnetic elements at London showed notable discrepancies for other places on the Earth when compared with the actual values observed at these places. Also, the distribution of magnetic meridians and isogonal lines on the magnetarium was more regular than the actual terrestrial ones. In order to remedy this Wilde conceived the very original idea of covering those portions of the surface of the magnetarium which represented the oceans with layers of sheet iron of a suitable thickness cut to shape. The result was remarkable. Not only did the instrument reproduce exactly the actual values of the magnetic

elements at the various portions of the Earth's surface, even for stations as widely separated from one another as London, the Cape, and St. Helena, but it also showed, for the same stations, the secular variations of the elements. Furthermore it even reproduced the oval of Eastern Siberia, in the interior of which the declination is westward, and also the oval of minimum declination observed in the east of the Pacific near the neighbourhood of the equator.

Thus, for the first time, a natural phenomenon of so great a complexity as that of terrestrial magnetism, has been reproduced artificially in every detail, not only as regards its distribution in space but also showing the secular variations which occur in time. We cannot look with indifference upon the theoretical considerations which have led to a result that is so remarkably in accordance with the natural phenomenon. In particular, what is the reason of the rôle of magnetic screen played by the seas? We know that the oceans exert a very great influence upon the atmospheric circulation and climatology in general. What is the nature of their mysterious influence upon the distribution of terrestrial magnetism? Perhaps it is a consequence of a state of affairs corresponding to Lippmann's

theory, viz., that the thickness of the terrestrial crust is less under the oceans, so that in these parts the internal ferruginous materials are nearer the surface of the geoid than elsewhere, and consequently play the same part as Wilde's screens.

So once again, as we have already seen in the study of gravity and the form of the Earth, and as we shall see later in connection with general meteorology, the solution of the problems of the physics of the globe will probably be found in the study of the oceans. Prince Albert of Monaco clearly foresaw this when he founded the Oceanographical Institute.

In any case, we see the importance of the initial conception of distinguishing the magnetic action of the nucleus from that of the crust. Bauer, who superintends the magnetic work of the Carnegie Institution, also believes, as a result of studying Gauss's conclusions, that the terrestrial magnetism resides almost entirely in the solid crust which envelops the nucleus.

To summarise, the Sun's action is paramount as regards the electric and magnetic phenomena of which the terrestrial globe is the seat. We do not yet know, however, whether these phenomena are wholly due to the solar field or whether the latter merely modifies them. In other words, is the

Sun's action sufficient to give rise to the Earth's magnetic field or, on the other hand, does this latter pre-exist, caused by some original and as yet unknown cause, only its variations arising from the variations of the solar radiation? What *is* quite certain, is the actually proved connection between the variation in the number of solar spots on the one hand and magnetic variations, variations of earth currents, of magnetic storms, of the number of polar auroræ, and frequently of the number of seismic phenomena. This shows that, even if we must not seek the cause of terrestrial magnetism in the Sun (which we have not yet been able to prove), we must, at any rate, look there for the cause of the variations to which its numerous phenomena are subjected.

# CHAPTER IX

## THE RHYTHMIC MOVEMENTS OF THE OCEAN, TIDES, SWELL, AND WAVES

THE manifestations of the life of the terrestrial globe, its general movements, the perturbations it is subjected to, the spasms of its crust, and the manifestation of electricity and magnetism which traverse it, as well as all that communicates this incessant restlessness to the Earth, have their origin in the Sun.

But our globe is not composed entirely of its lithosphere; the hydrosphere which covers more than three-fourths of its surface has an importance of which we have already seen something, for example, in connection with the distribution of terrestrial magnetism. We shall now study the movements of the hydrosphere, and here again we shall find evidence of solar influence, either the direct action of the attraction of its mass, or the indirect action of the heating of the molecules of the fluid substances water and air, enveloping the Earth's crust, and from which results the general

movements that are the origin of the circulation of the oceans and the circulation of the atmosphere.

It is hardly necessary to recall the facts concerning the importance of the sea in the general economy of the globe. In the first place it occupies more than two-thirds of the surface; out of the 510 millions of square kilometres [194 millions sq. miles] of the terrestrial crust 365 millions [138 millions sq. miles] are covered by water. There is thus far more water than land, and to the oceans, like bodies elected by universal suffrage, must accrue the rights of the majority. The great atmospheric conditions become established, not above the smaller part of the Earth's surface exhibiting the innumerable accidents of the geographical relief, but above the vast uniform oceanic surface the molecules of which freely obey the laws of fluid mechanics.

The total volume of the water of the oceans is about 1300 million cubic kilometres [309 million cubic miles], while that of the emergent dry land is only 100 million [24 million cubic miles]. The mean depth of the seas is about 3550 metres [2.2 miles]. All this mass of water contains a quantity of salts in solution and also, doubtless, metals in a state of extremely fine division. This

will be readily understood since, the seas, in the first instance, were formed by the collection of the boiling water-streams which condensed from the Earth's primitive atmosphere and were precipitated on the scarcely solidified crust. In such conditions, the water would have dissolved all that was soluble on the surface of the Earth. Sea-water should thus contain all known substances, at any rate in traces. The mean quantity of salts contained in a kilogram [2 lb. 3 oz. 4 dr.] of sea-water is 35 grams [1.25 oz.] and 75% of this total salinity is composed of sodium chloride, that is to say, common salt. The salt in solution in all the seas would provide enough material to construct the African continent in all its relief. With the gold, of which only a few milligrams [a few hundredths of a grain] are contained in a ton of water, a block could be made which, if divided equally among every inhabitant of the Earth, 1,500,000,000 in number, would give to each one an ingot of 40,000 kilograms [44 tons] of the precious metal, or in other words a fortune of 120 million francs [24 million dollars]!

The salinity of the oceans increases their density; a litre [1.05 quarts] of sea-water weighs 1 kilogram [2 lb. 3 oz. 4 dr.] and 28 grams [432.1 gr.] instead of 1 kilogram as pure water does. One

can therefore swim more easily in it as it possesses a greater buoyancy.

The greatest depth revealed in the course of the Pacific soundings is actually 9750 metres [6 miles]. The continents seem to lie on a kind of base, known as the continental plateau, the mean distance of which below the surface is 200 metres [650 ft.]. Beyond the immediate neighbourhood of the continents, the depth rapidly increases, and this applies equally to the Atlantic, the Pacific, and the Indian oceans. In the case of the Mediterranean, the Straits of Gibraltar, dominated by the Rock, impose special temperature conditions, but in all other cases the temperature falls in proportion to the depth below the surface, and when depths of 6000, 7000 and 8000 metres [3·75, 4·35, 5 miles] are reached it is found that the water there has a uniform temperature in the neighbourhood of zero [0°C. = 32° F.]. Here we find ourselves in the presence of one of the paradoxes of terrestrial physics. If we bored into the Earth's crust to a depth of 8000 metres [5 miles] we should find a temperature of about 240°–250° C. [400°–420° F.] at the bottom of the shaft so made, while at the same depth under the seas the result is 0° C. [32° F.]! The difficulty is increased by the fact that the crust, which is

presumably of less thickness under the oceans, consequently offers less resistance to the transmission of the internal heat. The explanation is doubtless to be sought for in the stream of cold water coming from the polar regions, which on account of its greater density falls to the bottom of the great oceanic hollows. Then when the water becomes warmed to above zero [32° F.], it rises by a process of convection, thus producing a vertical oceanic circulation; the water so coming up is replaced by more cold water from the polar regions.

The movements of these waters constitute one of the most imposing manifestations of the "life" of the globe; by passing a few days on the Brittany coast we can not only admire the magnificent phenomena of the tides, but are also enabled to conceive the immediately apparent laws governing them.

We see, at a certain time, the level of the sea rise in a continuous manner, constituting what is called the rising tide; at the same time the water of the open sea advances towards the land, and this current is known as the flood-tide or the flow. Gradually, the rise of level stops and the flow ceases, the water finally remains stationary at its highest point. It is now the time of high tide.

Subsequently the current recommences in the opposite direction, the water flowing from the land towards the sea; this is the ebb. The level of the sea gradually falls, and that part of the land covered by the rising tide reappears. The falling tide becomes more rapid up to a certain limit, and then its rate decreases and finally ceases altogether, the water having reached its lowest level. This is the epoch of low tide. Soon the process of rise begins again and passes through all its former phases, constituting a second high tide, followed by a second low tide some hours after.

If the phenomenon be watched for several days it may be shown that there are, broadly speaking, two high tides and two low tides daily, but the interval of time between them is not an exact subdivision of a day. Thus, if a high tide be noted at eight o'clock on the morning of a certain day, the high tide of the next day will not occur at eight o'clock but at ten minutes to nine. The interval separating the two high tides which takes place during the same day is not 12 hours but 12 hours and 25 minutes, the difference being half the above. The diurnal period of the tide is thus 24 hours 50 minutes. Now, this is precisely the value of the interval of time separating two successive passages of the Moon over

the meridian of the place. We hence see that the Moon is a dominating factor in tide-production.

It will further be observed that at any one place on the coast the water at the moment of highest tide is never at quite the same level on any two following days. For several days the tides increase in height from one day to another; this is the period of spring-tides. Then follows a period when the level of the high tides is less each day; this is the time of neap-tides. Observation shows that the periodicity of spring-tides and neap-tides is the same as that of the phases of the Moon, and these latter depend on the relative positions of the Moon and the Sun with regard to the Earth. Consequently, although the Moon is the principal factor which governs the tide period, the Sun also has an effect which modifies the magnitude of the phenomenon.

There is another observed fact which is noteworthy, viz., that the height of the tide may have very different values on the same day at two points of the Earth which are close to one another and which are therefore at the same distance from the attracting bodies. For example, if we find a tide at Granville, of 6.11 metres [20 ft.] on a certain day, the height of the tide at the neighbouring port of Cherbourg on the same day will

only be 2.82 metres [9.2 ft.]. There is, therefore, a geographical factor which influences the phenomenon and which arises from the coastal configuration at the place considered. Finally, it may be proved that high tide at any given place does not take place exactly according to the astronomical attractions arising from the position of the Moon and of the Sun; it takes place some time afterwards and the time-interval of retardation is constant for each place. For any port this is called the establishment of the port. The greatest establishment of the port in France is 12 hours 30 minutes, at Dunkerque; the smallest is at Lorient, viz., 3 hours 32 minutes. Here again the geographical configuration of the coasts and the irregularity of the sea-bottom have an important influence.

It was Newton who first gave the explanation of the beautiful phenomena of the tides. The Moon, on account of its proximity to the Earth, attracts the molecules of the water in the oceans that are situated on the side of the Earth facing it, to a greater extent than it attracts the centre of the globe and this latter is attracted more than the molecules of water situated on the opposite side of the Earth. We, thus, find at the free surfaces of the seas two liquid protuberances, the summits

of which are situated on the line which joins the centre of the Moon to the centre of the Earth. The first is due to the attraction towards the Moon of the fluid mass lying on the side nearest it; the second, on the opposite side arises from the fact that the centre of the globe is more strongly attracted, being nearer the Moon, than the water on the far side which is, so to speak, left behind and hence forms a protuberance (Fig. 27).

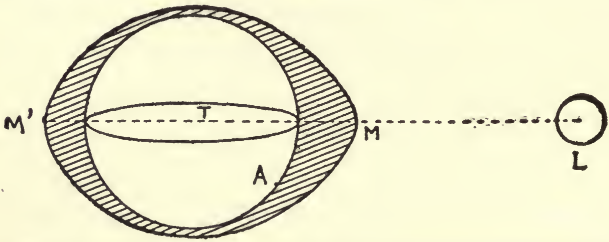



FIG. 27.—Tidal Prominences produced upon the Seas by the Attraction of a Neighbouring Body.

When the Sun is in the same direction as the Moon with respect to the Earth, that is to say at the epoch of syzygy, their attractive forces are additive; when the two bodies have their centres on the two sides of a right angle formed at the centre of the Earth, that is to say at the epoch of quadrature, the attractions oppose one another. We have seen, in studying the deviation from the vertical under the influence of the luni-solar attraction, that if we represent the Sun's attrac-

tion by 1, that of the Moon is approximately equal to 2. The tide would thus have theoretically for relative amplitudes 2 + 1, *i. e.*, 3 at the epochs of spring-tides and 2 − 1, *i.e.*, 1 at the epochs of neap-tides.

This explanation of Newton, based on the equilibrium between the lunar attraction and gravity, gives an account of the phenomenon in its broad outlines and general details, but is found wanting when certain observational facts are taken into consideration. For example, if we apply the theory of static equilibrium to the calculation of the height of the liquid protuberance which represents the tide, we obtain a result of 35 centimetres [13.75 in.]. Now, the most cursory observation shows that the variations of the level of the sea under tidal influence have much greater values than this. In the ports of the English Channel and Brittany the variation is several metres; at Mont Saint-Michel, at the epoch of spring-tides, the difference reaches 14 metres [46 ft.], while in the Straits of Magellan it attains 18 metres [59 ft.], and in the Bay of Fundy, on the coast of Newfoundland, 21 metres [69 ft.].[1]

[1] At Chepstow on the River Wye in England occurs the highest tide in the British Isles and probably in Europe; it has been known to attain a height of forty-seven ft.—*Trans.*

Furthermore, in certain regions, for example, in Polynesia or in the Gulf of Tonkin, there is only one tide daily instead of two.

Consequently the simple consideration of equilibrium between the astronomical attractive forces and the terrestrial gravity do not suffice to explain the amplitude of the tide; neither do they satisfactorily account for the observed retardations, nor for the differences between two neighbouring places. It will, therefore, be necessary to seek for the complete explanation of the tides, not in the law of fluid equilibrium, but in that of their movements, or in other words not in the study of hydrostatics, but in that of hydrodynamics.

We shall once more find Laplace's genius the starting point of this theory. The illustrious mathematician recognised that when the luni-solar attraction influences the water of the oceans, this attraction, which is exercised by two bodies that move with respect to the Earth, should give rise not to a fixed protuberance, a liquid hill so to speak, but to a true undulation which would move over the sea surface in accordance with some more or less complex law, depending on the nature of the relative movements of the attracting bodies, on the angular variations of their positions with regard

to the Earth, and on the variations of actual distance from the Earth. Thus, since we are led to consider wave propagation, we must study the matter from the point of view of fluid dynamics, taking account of the resistances of fluids. Two fundamental principles govern this study, first that of the superposition of small movements and secondly, that of periodicity. The enunciation of the first is as follows: Let us start with the assumption that a system of material points is in equilibrium, and that a very small force is applied so as to disturb this equilibrium. Then, a material point will be given a small velocity, so small that the expression of the force depends only on the time and the mean position of the point. In these conditions, if several forces act simultaneously, the laws of mechanics show that at each instant their effects are independent and consequently superimposable. Also, as these momentary effects have no influence upon the forces themselves, it follows that the total effect will be the sum of the partial efforts calculated as if each force acted separately.

This first principle is of extreme importance; it enables us to consider separately the influence of the Moon and the Sun. That is if we evaluate on the one hand the solar tide and on the other

hand the lunar tide, we get the resultant tide by adding the two together. All optical and acoustic phenomena are illustrations of this principle; light and sound waves proceed through space without mutual interference, and, at the present time, trains of electric waves rapidly travel above the Earth's surface, propagating themselves in all directions without the one in any way hindering the others.

The second principle is that of the periodicity of movements caused by periodic forces: Every periodic force produces periodic movements in the group of molecules on which it acts. The periods of the force and resulting movement are equal and at a given point their difference of phase is constant. Thus, a body which travels uniformly in the plane of the equator, remaining always at an invariable distance from the Earth, would give rise, by its relative diurnal movement, to perturbing forces having a period of half a day. In any place whatever, the variations of the level of the sea resulting from this action would have, according to the second principle above, exactly the same semi-diurnal period, and the diverse phases of the movements would be displaced relatively to the corresponding phases of the force by a constant interval of time.

The relative movement of the attracting bodies, however, does not take place in so simple a manner as this, and, leaving the other elements out of consideration, the fact of the inclination of their apparent paths to the plane of the terrestrial equator necessitates the addition of two other categories of forces to those of semi-diurnal period. These other forces are diurnal and long period forces respectively.

In the first place, the action of a body turning only around the Earth will be of semi-diurnal period, for the result is the production of two tide wave-summits diametrically opposite one another. The terrestrial diameter which joins these two summits follows the orbital movement of the body. In these circumstances, the two waves travel around the Earth in such a way that, in the course of the twenty-four hours, which is by supposition the period of the body's movement, a point A of the Earth will be twice affected by the tide wave, viz., once by the wave M and once by the wave M′ (Fig. 27). The period will be semi-diurnal. This is what would occur if the body was in the plane of the equator and at a constant distance from the Earth.

But the body is not usually in the plane of the terrestrial equator. In the general case it is

outside this plane, either above or below it. Consequently the two zones of deformation M and M′, through which every point of the Earth passes in its diurnal movement, are unsymmetrical. These two protuberances have therefore unequal effects, and this inequality is represented analytically by the superimposition of a movement of the sea, of diurnal period, on the semi-diurnal wave of which we have previously spoken. We already see that there will be a considerable number of waves; in fact, if we take as unity the solar day, we shall have, on the one hand, to express the Sun's action, a solar day of 24 hours and a semi-solar day, and for the Moon, on the other hand, a lunar day of 24 hours 50 minutes and a semi-lunar day of 12 hours 25 minutes.

The orbits of the two bodies are, furthermore, inclined to the plane of the terrestrial equator; the charges to which the declinations of the Moon and Sun are subjected from one day to the next are accompanied by little variations in the respective durations of the true solar day and the lunar day. This has an effect on the amplitude and period of the diurnal and semi-diurnal undulations. We must next note that the Moon and the Sun are not at constant distances from the Earth, owing to the ellipticity of the orbits of the Moon and

Earth. There is a variation to the extent of $\frac{1}{18}$ part in the case of the Moon in a month, and one of $\frac{1}{60}$ part in the distance of the Sun from the Earth in a year. This is another cause of modification of the amplitude of the solar and lunar undulations, and the result is as if we combined with each of the principal waves, of their average amplitude, two subsidiary waves having as amplitude the semi-difference between the mean and the maximum, and for respective velocities the sum of and the difference between the principal wave and the variation of amplitude.

We have already mentioned that long period waves are superimposed upon these diurnal and semi-diurnal ones, and the period of each of these new waves depends on the duration of the apparent revolution of each of the attracting bodies round the Earth. Consequently, for the Moon there is a fortnightly wave and a monthly wave, and for the Sun a half-yearly wave and a yearly one, but their amplitudes are much less than those of the principal waves.

This is not all; we have seen in studying the Earth's movements that the place of the lunar orbit suffers a recurrent displacement, and that its intersection with the plane of the terrestrial orbit is continually being displaced from west to east,

executing a complete turn in 18½ years. As this must be taken into account in considering the inclination of the lunar orbit with respect to the terrestrial one, it will readily be understood that two new subsidiary waves are introduced, the one having a period of 18½ years and the other a period of half this, but being of very small amplitude. Other causes affecting the tides are the precession of the equinoxes, the Earth's polar displacements, and, in general, all the Earth's movements, but these waves are negligible in amplitude.

The complete understanding of the tides thus necessitates the calculation of the elements of each of these waves separately and the final combination of their periodic actions. Lord Kelvin and Sir George Darwin have carried out this work, using the beautiful method that is called "harmonic analysis," and, in France, the hydrographer Matt has also made a careful study of the matter.

In order to represent each one of these waves separately, we imagine for each one a fictitious astronomical body, supposed to be the only body in the Earth's presence, turning around the latter with a period equal to that of the wave it represents, remaining always in the plane of the equator and at a constant distance from the

terrestrial globe. This fictitious body, the mass and distance of which may be calculated from astronomical data, therefore always produces a constant, unique wave. The characteristics of as many fictitious bodies as there are elementary waves to be combined are thus calculated. The list of the principal ones is as follows:

The semi-diurnal waves are first the mean lunar wave, which represents the mean movement of the semi-diurnal tide. This is the most important one of all, and the fictitious body that would engender it would have a mass equal to $\frac{95}{100}$ of that of the Moon; secondly, the sidereal wave (lunar fraction) of period equal to a semi-sidereal day.[1] This gains on the first wave above, which is regulated by the lunar day, and the two coincide once in approximately fifteen days; thirdly, the lunar elliptical wave, which lags behind the first by a quantity equal to the mean anomalistic motion of the Moon in its orbit; the two coincide therefore at intervals of one month; fourthly, a mean solar wave; fifthly, a sidereal wave (solar fraction); and sixth a solar elliptical wave, the last three bearing the same relation to the Sun's action as the first three do to the Moon's action.

[1] The *sidereal day*, the period of one exact revolution of the Earth, is 23 hours 56 minutes 4.09 seconds long.—*Ed.*

Next, we come to the group of diurnal waves, first, a lunar diurnal wave and, secondly, a sidereal diurnal wave (lunar fraction), thirdly, a solar diurnal wave and, fourthly, a sidereal diurnal wave (solar fraction) which represent almost exactly the effects of the respective declinations of the Moon and the Sun. These waves are, taken two by two, of almost equal magnitude, so that at the epochs of their coincidences the effect of each of the groups is sensibly doubled, while at the intermediate epochs the two nearly neutralise each other.

To these astronomical waves, we must add others of different characters. In the first place; there are meteorological waves, the result of regular diurnal and seasonal winds on the tides; these are inseparable from the diurnal and annual solar waves. Secondly, there are the waves resulting from the complications that the more or less irregular conformation of shores and depths impose on tidal phenomena. This is especially the case in estuaries where the tidal flow traverses large but shallow spaces.

Thus, each one of these waves (we may enumerate sixteen for the tides on the coasts of France, and twenty-one for the tides of the Indies) may be imagined to correspond to the action of a fictitious body, the characteristics of which can

be calculated. It now remains to combine all these individual waves into one resultant whole. If this had to be done by calculation only, the work would be of great length and extreme difficulty, but Lord Kelvin originated the clever and simple idea of bringing the aid of a mechanical arrangement to the solution of the problem. He constructed an apparatus called the tide-predicter; when the particulars of each of the component waves are known for any given place such as, for example, Brest, the tide-predicter enables us to combine them all into a unique, complex, but mathematically exact curve which graphically represents the resultant phenomenon, that is to say, at the time represented by the abscissa of a point on this curve, the amplitude of the complex tide-wave which is the resultant of the composition of all the individual wave-elements is represented by the ordinate of that point.

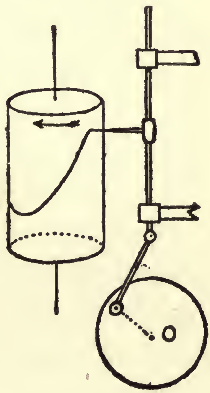



FIG. 28.—Tracing of a Sine-Curve by Combination of Revolving Drum and Rod and Crank Movement.

The illustrious English physicist utilized, in the construction of this apparatus, the fact that the curves which express tide-

waves are sine-curves, and that every sine-curve can be very easily traced by a pencil actuated by a rod and crank movement, the two trains of the crank and the revolving drum being connected (Fig. 28). If, therefore, we wish to compound a certain number of sine-curves each

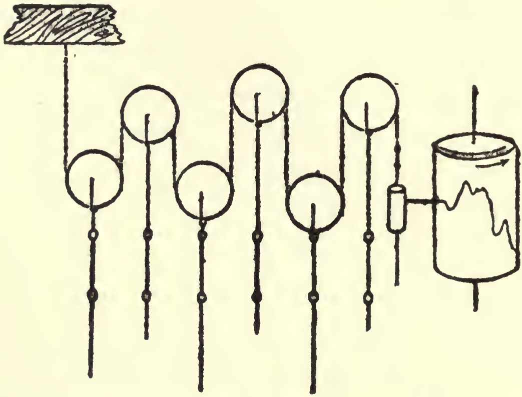


FIG. 29.—Principle of the Tide Predicter: combining Six Elementary Waves.

of which represents an elementary wave, say, for example, six, we take six crank rod systems (Fig. 29); the length of each crank represents the amplitude of the corresponding wave; the velocity of its rotation is governed by the period of the wave in question. Suitable trains of wheels enable each to be rotated by a separate movement with its correct individual velocity. The position that each crank occupies in relation to that

which represents the lunar, semi-diurnal wave when the latter is vertical shows the phase or relative displacement of the corresponding wave.

Each rod thus rises and falls, and if every one carried a pencil it would trace graphically on a paper, passing with a uniform motion, the sine-curve which is the graphical representation of the wave to which it corresponds. In order to combine all these movements to obtain the total effect, as regards both sign and magnitude, Lord Kelvin furnished each rod with a pulley. The rods are separated by spaces equal respectively to the diameters of the pulleys. One single thread passes through the grooves of all the pulleys; it is fixed at one of its ends and at the other end it carries a weight furnished with a pencil. When the whole system is started working it will be obvious that the weight, in rising and falling, represents at each instant the resultant ordinate of each of the partial ordinates of the six component sine-curves. If the pencil touches a cylinder covered with paper and turning uniformly, the required curve expressing the resultant phenomenon will be traced upon the paper. In reality there are sixteen pulleys in the apparatus in actual use for hydrographical purposes corresponding to sixteen component waves.

Such is the marvellous instrument which can do in a few minutes, exactly and without effort on our part, what would necessitate months of long calculations to achieve.

Before this apparatus was invented, and it dates back only a few years, tide almanacs, which are so necessary to sailors, had to be prepared in advance. At a given place the local circumstances, coasts, estuaries, the sea-bottom, etc., which so greatly influence the tides, are the constants for that place; the only variable quantities are the respective positions of the Earth, Moon, and Sun. Now every 18 years and 11 days these three bodies return to exactly the same relative positions. Consequently if the heights of the tides be observed at a given place during a period of 18 years and 11 days by means of the instruments called tide-recorders or tide-measurers, which are based on the principle of communicating vessels, we obtain the values of the tide for each day of the following period. This eighteen years and eleven days period was known to the ancients, who called it the Saros; seventy eclipses always occur during it, forty-one of which are of the Sun and twenty-nine of the Moon, and the eclipses observed during this period reoccur at corresponding epochs during the following period.

The tides propagate themselves in the form of a wave, and are consequently similar to the seismic waves of translation of which we have spoken in Chapter VII. Their velocity of propagation is, therefore, proportional to the square root of the depth of the water at the surface of which they are travelling. This explains a very curious observed fact: when the tide arrives at the west coasts of France the water rises slowly at first, from the level of low tide, but the velocity increases little by little and in proportion as the level rises the tide-stream is accelerated, the incoming current getting very strong and the rate of rise very rapid. This is a consequence of the above law of wave propagation, for the depth is nothing at first, at the time of low tide, and it increases in proportion as the sea recovers the sloping parts of the shore, being greatest just at the hour of high tide.

A similar consideration enables us to understand why there are at certain places, St. Malo, for instance, tides reaching a height of 14 metres, [46 ft.] while the theoretical tide ought not to surpass 60 centimetres [23.5 in.]. The explanation is that the tide manifests itself by an undulatory movement which communicates a considerable vibration velocity to the molecules of the water. So long as the wave travels over a

deep ocean, for example, at the surface of depths of water of 4000, 5000, or even 6000 metres [2.5, 3, 3.75 miles] the velocity of propagation is sensibly constant. But, when the wave of the tide approaches the coasts of Europe it meets the continental plateau which is a kind of base or foundation on which the European continent stands, only 200 metres [660 ft.] below the surface of the sea. The force of the incoming tide is therefore communicated to a much smaller liquid mass, and this results in the very high elevation of the water along the coasts, particularly in the English Channel, the narrow form of which accentuates the phenomenon. Maps may be made enabling us to follow the stages of the arrival of the tide-wave by the tracing of co-tidal lines joining the places where the wave arrives at the same time. The more the co-tidal lines are compressed together the greater the accentuation of the tides.

Two English hydrographers, Whewell and Lubbock, have carried still further this idea of the undulatory transmission of the tide. According to them, in order that the phenomenon of the tide-wave may be produced, it must take rise on an illimitable ocean in such a way that the wave following the movement of the attracting body can freely make the entire tour of the globe. Now

these conditions are only realised in the southern ocean in the vast and terrible sea which completely surrounds the terrestrial globe and is bounded by the Antarctic continent, lying between this and Cape Horn, the Cape of Good Hope and Australia. Whewell and Lubbock believe that it is here that the generating tide-wave takes rise without any continental obstacle. The tide-wave which occurs in the Atlantic would, consequently, be only a secondary wave derived from the principal one.

Facts have been observed which give a strong support to this original idea. All along the Atlantic coasts, even on the extreme south coasts of the Argentine, are stations at which the tides are noted. It is, thus, possible to follow hour by hour the propagation of the northward travelling tide-wave. Now it has been shown that, when the tide-wave arrives, for example at midday, at the Straits of Magellan, it reaches Cape Corrientes near the mouth of the Rio de la Plata at midnight, that is, twelve hours later. After another twelve hours it gets to the Canary Isles and finally twelve hours later, that is to say at midnight on the second day, its influence is felt in the tide-recorder at Brest. It has, therefore, taken in all thirty-six hours to cross the Atlantic from south to north. It can also be proved that at Brest the equinoctial

tide is only felt thirty-six hours after the theoretical moment when the Moon and Sun, whose attractive forces are then additive, produce the maximum possible tide. This is a very remarkable confirmation of Whewell and Lubbock's theory. Nevertheless, there is also a fact which runs counter to this theory. At no part in the islands of the Southern Sea, whether at Kerguelen, St. Paul, or New Amsterdam has the age of the tide been found to be nothing at all, as it should be in accordance with the preceding theory. *Adhuc sub judice lis est.*

Thus, the phenomenon of the tide is ruled, as regards its amplitude, by coastal configuration. In Europe, it is around England and France that the greatest variation of level takes place. Landlocked seas, on the other hand, such as the Mediterranean and the Baltic, have only insignificant tides; in the Gulf of Gabes tides of a metre [or yard] are sometimes observed and these arise chiefly from the Atlantic tide coming through the Strait of Gibraltar. On the other hand, in the partially landlocked seas and on large lakes, continuous variations of level are observed, the periodicity of which, although real, has no astronomical cause. These effects are readily visible on the Lake of Geneva. Their origin is

probably meteorological; when the atmospheric pressure distinctly increases at one end of an elongated lake, the level there is caused to fall and consequently that of the other end rises. Such a momentary inequality of the surface level leads to a re-establishment of hydrostatic equilibrium by means of a series of oscillations the duration of which depends on the size of the lake and its depth; theory and observation have always been in accordance on this point.

Seas such as the Ægean show also tide effects similar to that of the Lake of Geneva, and, at the epoch of the equinoxes, the joint effect of these and the small true tides which then occur is perceived. The variations of level have thus a complexity, more apparent than real, which the preceding considerations now enable us to elucidate completely.

The tides, as we have said, give rise to flow- or ebb-currents, according as the water is rising or falling. The configuration of the shore may be such as to be favourable to their establishment, or, on the other hand, it may tend to lessen them. In the former case, they may attain considerable strength and may present, at certain times, dangers for navigators. As cases in point we have the race at Sein in Finisterre, and the Blan-

chard race in the English Channel, where during the equinoctial tides the velocity of the current exceeds eight miles per hour, and the whirlpools which occur in certain places after the change of the tide, on account of the meeting of two contrary currents, such as the Maelström in the north of Norway, Corryvrekan in the Hebrides, and the legendary whirlpool of Charybdis, more dangerous in the fable than in reality.

We shall now deal with other rhythmic movements exhibited by the waters of the sea, viz., the swell and the waves.

A representation on a small scale of the propagation of waves over the surface of water may be obtained by letting a pebble fall into a basin of water. Circular ripples or undulations are seen moving outwards from the point of immersion of the pebble towards the edge of the basin. The same thing occurs on a large scale at the surface of the oceans, which are always traversed by undulations of more or less importance. Such a movement is that produced in calm weather. When the wind begins to freshen and rise, the ridges of water which constitute the undulations of the swell lose their beautiful regularity; they cease to be symmetrical, becoming steep while

their surfaces are covered with ripples and subsidiary wavelets. Little by little, under the influence of the wind, the wave slopes become hollowed and the summits begin to overhang; finally they give way and fall over, imprisoning a mass of air which escapes in bubbles of whitish foam, constituting the white-crested waves familiarly called "white horses." These are breaking waves.

The height of waves is sometimes considerable. While not reaching the values of 40 and 50 metres [130 to 150 ft.] which the assertions of ancient navigators attributed to them, on account of an optical error into which it is easy to fall, they do actually attain in the Southern Seas, at their highest, 15 to 16 metres [50 to 55 ft.], 10 to 11 metres [35 to 40 ft.] in the Indian Ocean, 8 to 9 metres [30 to 35 ft.] in the Atlantic, and, finally, in the Mediterranean 5 to 6 metres [15 to 20 ft.], always speaking of their highest, and, when freely propagated, far from the coasts.

For, when a system of undulation is not freely propagated but meets an obstacle, the phenomenon is complicated by that of interference between the direct movement, and the one reflected from the obstacle. In this way, the height of waves may become enormous. This is what happens

when they beat upon the coasts; they rise up to heights of 40 to 50 metres [130 to 150 ft.] and fall back in masses of foam. The same thing happens when a large vessel is going at full speed in the opposite direction to the movement of propagation of the waves; these dash over the bow and may reach even to the highest superstructure when they sometimes do damage or wash away men.

When several series of waves, travelling in different directions, meet together, as a result of some special circumstances, interference phenomena are again produced, and the sea becomes agitated and choppy. This occurs at the centre of cyclones, where thousands of undulatory movements meet together, engendered by winds that have every possible direction since they form part of a whirling movement. In the Mediterranean, the closed contour of the coasts gives rise to reflected movements in all directions, and consequently the sea presents short and choppy waves which often render navigation difficult, although it is not actually very agitated.

The length of waves between consecutive summits is about 20 to 30 times their height; the great waves, 15 metres [50 ft.] in height, of the Southern Seas may thus reach lengths of 300 to 450 metres [325 to 500 yds.]. Consequently, the

slope of these liquid heights is quite a gentle one, and this circumstance is a fortunate one, for, without this, the falling over of the crests when they break would render all navigation impossible.

If only a superficial examination be made, it seems that when undulations of water are caused in a basin, the water itself is transported towards the edge of the basin. More attentive observation will, however, show that this is not the case, for a small piece of wood thrown on the surface of the water rises and falls alternately with the passage of the waves, but does not move any nearer to the edge. The molecules of the liquid, therefore, move up and down in one place; two German physicists, the brothers Weber, have experimentally studied the matter and have found as a result that each

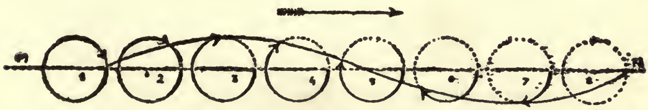


FIG. 30.—Circular Vibratory Motion of a Molecule of a Liquid (Formation and Propagation of a Swell).

aqueous molecule describes a closed curve (Fig. 30), and that it is the combination of these vibratory movements, transmitted from molecule to molecule which constitutes the propagation of undulatory movements. In proportion as the molecule in question lies deeper under the water,

the circular path described by it is flatter and so becomes a more and more flattened ellipse which, ultimately, is reduced to a straight line. At great depths, therefore, wave propagation takes place by a simple rectilinear horizontal movement, forward and backward, of the molecules of the liquid. Experiment has shown that surface agitations make themselves felt down to a depth of 300 to 350 times the height of the undulations produced; there is, thus, a level below which superficial agitation is practically not transmitted at all.

The most simple manifestation of undulatory movement at the surface of the sea is the swell characterised by the absence of that white foam which sailors call "white horses." It forms at the surface of the sea regular ridges, with regularly curved sides and which move majestically over the water when the atmosphere is calm.

The undulation of the swell is in profile the curve above represented and is called by mathematicians a cycloid. Such an undulation is characterised by its length, by which is meant the constant distance between two consecutive crests; by its velocity of propagation, which is the distance traversed in a second by the condition of undulation; by the period, which is the time taken for one crest to succeed the next, and, finally, by the

amplitude or height of the undulations, that is to say, by the vertical distance between the crest and the hollow of the wave.

The movements of the sea represent the production of a considerable sum of mechanical energy.

Considering first the waves, their velocity of propagation is about twenty-five marine miles per hour, that is, more than 45 kilometres [28 standard miles]. Furthermore, a large mass of water is contained in a wave 10 metres [35 ft.], high, and, as the energy of the wave is its mass multiplied by the square of the velocity, it so attains a considerable amount. A wave of the height and velocity just mentioned develops about two thousand horse-power per metre [or yard] width. Stephenson has also measured directly the force exerted on a given surface by the shock of such waves and finds it thirty tons per square metre [French ton=2204.62 lbs.]. If we remember that a like force is produced every ten or fifteen seconds, this being approximately the period of these waves, for periods of some days, it is obvious that they represent a large amount of energy.

These powerful masses of water beat against the coasts, and by long-continued attack wear away the rocks and break off portions of them. In this

way the granites of Brittany are scooped and hollowed, and the chalk cliffs of Normandy are undermined from their base. Similarly defensive works and breakwaters that man has erected, at the cost of years of difficult labour, to protect harbours may sometimes be broken through and destroyed by a single storm in a few minutes. Perhaps, at some future time, it may be possible to harness these hitherto unutilised forces; then transmitted inland by means of electric currents, the movement of the waters of the sea could be put to use instead of, as at present, only causing destructive effects.

As regards the tides, the power represented by the alternate rising and falling of the level of the sea is also considerable, and would be easier to utilise; it would suffice to construct vast basins which could actually be done in many cases by closing in an estuary by means of a dam, forming a natural reservoir which would be filled at high tide by the flowing in of the sea. The opening could then be shut, and the water thus maintained at the high level would work turbines in rushing down when the level of the water outside had fallen; consequently the power would be available. In regions such as that of St. Malo, where the tides reach a height of 15 metres [50 ft.] at the

equinoxes there would be an ample reserve of energy. In the bay of Mont St.-Michel each square kilometre [.38 sq. mile] of the sea surface represents an average force of 20,000 horse-power, and the bay is not less than 300 square kilometres [116 sq. miles] in area. If, therefore, it was closed by an embankment we should have available about 6,000,000 horse-power, and the work would not be more difficult than the making of the Suez Canal or of a railway across the Sahara. And a number of other bays would lend themselves to similar procedure. The damming of the Rance would also give more than 200,000 available horse-power.

This enormous quantity of energy is produced by the periodic attractions of the Sun and Moon particularly of the latter. This seemingly dead world, therefore, gives rise to movement and force upon the Earth's surface. This is a beautiful example of the rejuvenation of everything, and of that evolution which we recognise everywhere in the study of organised matter. As has been so truly said, "Life is reborn out of death," and it seems probable that this applies to the life of worlds also.

# CHAPTER X

## THE CIRCULATION OF THE EARTH, MARINE AND ATMOSPHERIC

ONE of the characteristics of life is a continuous circulation in the body of the living being; animals and plants have such a circulation inseparable from their very existence. If we consider that the Earth "lives" and evolves it also ought to have its own circulation.

We have already seen that an electric circulation exists in the crust and its nucleus, and we have mentioned the convection movements which occur in the liquid superficial mass of its interior magma. We shall find in the course of this chapter that the two media which envelop it, the hydrosphere and the atmosphere, are both the seat of a continuous circulation, the importance of which, from the point of view of the exterior aspect of the terrestrial relief, is very great. We shall first consider the atmospheric circulation and then the oceanic circulation, and we shall see that these two pheno-

mena are connected by such a direct relationship that they are inseparable from each other.

Although the atmosphere does not possess the fixity of composition of a chemical compound, yet, at any rate in its lower layers, the composition is found to be very nearly invariable, viz.: 21% of oxygen, 78% of nitrogen, and 1% of argon, besides infinitesimal traces of other rare gases, such as xenon, neon, and krypton and also of hydrogen and helium. This percentage composition is by weight. We speak here only of the simple gases that are chemical elements in the accepted use of the term; that is, chemical elements in the sense in which the word was used prior to the discovery of radioactive phenomena, and in which it is still used to elements in the customary sense of the word, whether they may be transformed into simpler elements by radioactive process or not. Two of the gaseous compounds, carbonic acid and water-vapour, play an important part in the economy of our Earth. In speaking of the first stages of the Earth's existence, we have dwelt on the protective function which they fulfil in regard to the surface temperature of the Earth, constituting a thermal mantle. The remaining ones such as ammonia, nitrogen, and sulphur compounds, ozone, etc., are present in only very small

and variable quantities. The lower layers, in contact with the land and the seas, contain almost the same proportion of simple gases. The proportion of hydrogen and helium increases with height, and in the highest regions of the terrestrial atmosphere, the little air which remains is composed of 99% of hydrogen and 1% of helium.

These gaseous substances are subjected to two forces, first, the centrifugal force, in consequence of the Earth's rotation, and secondly, the Earth's attraction. Furthermore, they are constantly exposed to the thermal action of the solar radiation. Water-vapour is the best absorbent of these rays and so constitutes the principal agent in the heating of the air under the influence of the Sun's rays.

If the terrestrial globe were a surface without relief, wholly covered with a homogeneous substance such, for example, as sand, and if its axis of rotation were perpendicular to the plane of its orbit instead of being inclined, every point on the Earth would be subject to constant temperature conditions, save for the little variations in the distance of the Earth from the Sun in accordance with the law of Kepler. For every place on the globe throughout the entire year the days and nights would have an equal duration of twelve

hours. The temperature, which would be at a maximum in the region of the equator, upon which the Sun's rays would fall normally, would diminish regularly up to the poles, where these rays, grazing the surface, would have no heating power at all, since this depends on the sine of the obliquity. Consequently, there would be no seasons, and the different terrestrial climates, that is to say, the sum-total of meteorological conditions at each point of the globe, would vary from one place to another in a continuous way.

But in reality things are not nearly as simple as this. In the first place the axis of rotation of the Earth is not erect; the plane of the terrestrial equator makes an angle of 23½° with the plane of the ecliptic. From the resultant inclination, and, therefore, the existence of seasons and the inequality of the days and nights, the Earth is divisible into Geographical Zones: first, the Torrid Zone, through the centre of which the equator passes, and which comprises all places between the two tropics, those circles of latitude corresponding to 23½° North and South latitude respectively; secondly, the two Frigid Zones, the centres of which are occupied by the respective poles, comprising the regions between the pole and the latitude circle of 66½° North or South respectively;

lastly, the two Temperate Zones, which include all the regions between the Frigid Zones and the Torrid Zone.

Another factor making for complexity in the superficial heating of the Earth is the lack of homogeneity of its surface which is covered with water over nearly three-fourths of its area, while the dry part is characterised by a varied relief including mountains and valleys, high plateaux, depressions, and deserts. The nature of the soil, and therefore its absorbing power for heat radiation, varies from one place to another. Consequently, the heating of the atmospheric layer resting upon the soil will thus also vary from place to place.

As regards the oceans, which form the chief part of the Earth's surface, the matter is simpler, for their surface is homogeneous and without relief. The molecules of the fluid masses, water and air, can thus freely obey the laws which govern them—that is to say, those of attraction, centrifugal force, and equilibrium of gaseous substances. We should, therefore, find regular atmospheric conditions established over the great oceans, such as the Atlantic, the Indian Ocean, the Southern Seas, and especially, the Pacific. Now this is what actually occurs and we shall commence by saying a few words as to these conditions.

The tropical regions, viz.: those which belong to the Torrid Zone, are those most exposed to the solar radiation, for twice annually the Sun passes through the zenith of each of the places in this zone, at the moment when it is true noon at the place in question. The rays, therefore, fall perpendicularly on to the ground, and so have the maximum possible heating effect. As a consequence, especially along the equator, the atmosphere in contact with a warmer substratum is heated to the greatest degree in its lower layers. Furthermore, it is the lower layers which contain the most water-vapour and dust particles, and so absorb more completely the heat radiated from the Sun. There are, thus, two reasons why the equatorial atmosphere is relatively strongly heated. By means of instruments called bolometers the quantity of heat thus received annually by the equatorial belt has been measured. It has been found that it is sufficient to vaporise a layer of water four metres [12.2 ft.] deep covering the same area. Now meteorologists, on the other hand, have determined by means of observations extending over numerous years the average yearly quantity of rain which falls on the equatorial belt; it is represented by a layer of water two metres [7.5 ft.] in depth. Even admitting that the

whole of this water was vaporised by the solar heat, and that none of it soaked into the soil on which it fell, it is obvious that after complete vaporisation there would remain a surplus quantity of heat sufficient to vaporise as much again.

Nothing is ever lost in Nature's admirable economy. This surplus heat is employed for some other purpose, and that purpose is the further heating of the lower layers of the equatorial atmosphere. Thus superheated, and consequently of less density like the air in a fire balloon, these lower layers rise upwards to considerable heights. Also, this process is continuous, since the cause of the convection current, viz.: the equatorial heating, is always continuous. This is the fundamental movement of vertical circulation in the terrestrial atmosphere, and it gives rise to others, for in consequence of the uprising of masses of warm air towards the upper atmosphere, there is a rarefaction near the surface of the ground, with the result that masses of cold, dense air from the Temperate and Frigid regions flow towards the equator to take the place of that which has left it. If the Earth were at rest there would thus be northerly winds in the Northern Hemisphere and southerly winds in the Southern Hemisphere

blowing, in the direction of the meridians, towards the equatorial regions.

But the Earth is not at rest; its movement of rotation, as we have seen, produces a deviation of the path of any moving body in the Northern Hemisphere towards the right, and in the Southern Hemisphere towards the left. These winds, which in the imaginary case flowed in the north-south direction, are actually deviated and become north-easterly winds to the north of the equator and south-easterly winds to the south of that line. These are the trade winds, which carried the caravels of Christopher Columbus to the New World. To-day, the track of these regular winds is known; Maury, the father of Oceanography, was the first to draw up monthly maps which indicated to sailors routes shortening by half the duration of long voyages made by sailing vessels.

As regards the ultimate destination of the masses of warm air which leave the equator and rise into the upper atmosphere, they travel towards the poles and gradually sink down as they cool, replacing the air of the Temperate and Frigid regions which has moved towards the equator. These winds are called the anti-trade winds. Their existence is rendered manifest by the movement of the cirrus clouds, which are in the form of deli-

cate filaments and are more elevated than any other kind of cloud formation. Cirri always travel from the south-west to the north-east, in the Northern Hemisphere, driven by the upper returning air currents.

These anti-trade winds, which are also deviated by the Earth's rotation, gradually become westerly winds and finally merge into a current of air turning around the poles, adding their velocity of progression to the velocity which the Earth's rotation would impart to their molecules if they were originally at rest. The masses of air that they displace will thus turn around the poles with a velocity greater than that of the Earth itself, and a considerable centrifugal force is thus produced tending to throw the air outwards from the axis of rotation. Consequently, in the neighbourhood of this—that is to say, around the poles, there is a rarefaction or atmospheric depression, this time of mechanical origin.

Thus, there is a thermal depression at the equator and a mechanical one at the poles; between these two minima the principle of continuity necessitates the existence of a maximum of pressure. By calculation, this should occur at latitude 30° North and South, and observation confirms the permanent existence of this

high-pressure condition over the oceans in these latitudes.

We, therefore, have a complete circulatory motion of the air masses enveloping the Earth: the direct current from the Pole to the equator along routes inclined to the north-south direction on account of the Earth's rotation, and the return current in the upper regions of the atmosphere from the equator towards the poles.

The trade winds blow continuously, since their cause, the solar heating, is continuous. They gradually produce a similar movement of the molecules of water at the surface of the sea, since neither air nor water being perfect fluids, friction is exercised between their respective molecules; along the equator the molecules of the water being influenced in two ways at the same time, viz.: by the north-east trade winds of the Northern Hemisphere and the south-east trade winds of the Southern Hemisphere, follow the resultant direction of these movements which is from east to west. Limiting ourselves to the current traversing the North Atlantic Ocean, the direction is from the coast of West Africa to that of Brazil. This is the origin of the equatorial current which meets Cape St. Roque and, because of the form of the American coast, there divides into two

parts. One branch goes towards the south, which we will pass over for the time being; the other, which we shall follow up, goes northwards along the coast of Guiana.

One portion cf this branch, always composed of very warm water, passes outside the chain of the Antilles and then along the American coast, and being deflected towards the right by the Earth's rotation traverses the Atlantic Ocean in a slantwise direction from south to north. The other part enters the Gulf of Mexico and accumulates there under the thrust of the water which continues to flow in, the Gulf being almost closed. There it bathes shores heated by the tropical sun, and the temperature of the water consequently increases. Under the influence of the mass of water from the equatorial current that is continually entering the bay, this heated water leaves it by the only possible exit, viz.: the Strait of Florida, through which it escapes with a velocity of 4½ knots per hour, or in other words about eight kilometres. It, thus, enters the Atlantic again, and rejoins and reinforces the first northward-moving branch, giving to that current additional mass, greater velocity, and a higher temperature.

This current is called the Gulf-Stream, and it constitutes a river of warm water flowing between

two banks of cold water, as Maury has described it. On leaving the Gulf of Mexico, its depth is about 400 metres [1300 ft.] and its breadth 60 kilometres [37 miles]. In the latitude of Cape Hatteras, its depth is not more than 300 metres [1000 ft.], but, on the other hand, it is larger, and the width of its surface reaches 120 kilometres [75 miles]. It supplies 33,000,000 cubic metres [8720 millions of gallons] per second—that is to say, 2000 times more water than the Mississippi at its outlet, by means of which the ancient geographers formerly but erroneously sought to explain its origin. These warm waters carry along an enormous quantity of heat. This quantity has been calculated and is expressed by 39,500,000,000,000,000,000 calories[1] daily. This is equal to the whole of the heat which falls on one of the Frigid Zones during the six months when it is lighted and warmed by the Sun.[2]

This warm current forms the beginning of an oceanic circulation which completes itself by cold return currents, serving to replace the water

[1] A calorie is the amount of heat required to raise the temperature of one gram [15.432 gr.] of water through 1° C. [1.8° F.]. —*Ed.*

[2] A vivid comparison is that the Gulf-Stream transports as much heat as a stream of molten iron the size of the Mississippi River.—*Ed.*

which left the equatorial regions when warmed, and which becomes finally cooled near the poles. The most important of these cold currents is that of Labrador, which comes down the Baffin Sea and follows the coast of North America, the climate of which is the result of the Labrador current and is consequently very cold in winter. The current then plunges under the Gulf-Stream and reappears at the surface of the Atlantic again near the coast of Africa, thus favouring the abundance of fish along the African coast in the neighbourhood of the Walfish Bay, by cooling the high temperature of the sea in that part of the Atlantic.

Another cold current also descends along the east coast of Greenland, which is always fringed by pack-ice, rendering it inaccessible. The west coast of Greenland is bathed by a branch current derived from the Gulf-Stream, and is open to sailors during several months in the year; the Danes have established settlements on this coast. Floating wood from the tropics reaches as far as Disko Island, plainly showing that a current of equatorial origin has brought it there. It brings to the northern regions of the Atlantic, where the waters are always several degrees warmer than those which surround them, an enormous quantity of water-vapour which causes the persistent fogs which

occur over Iceland, Newfoundland, and the neighbouring ocean. These fogs lie in the path of transatlantic liners during the winter, and constitute a serious and permanent danger to navigation between Europe and America and also to the fisheries.

Such, in its broad outlines, is the oceanic circulation of the North Atlantic. An analogous case is found in the South Atlantic, which possesses a circulation of a similar kind. In the North Pacific there exists an important current, the Kuro-Siwo, the "black river" of the Japanese, which although less rapid and less warm than the Gulf-Stream presents in its entirety the same characteristics. The South Pacific and the Indian Ocean have also their circulation, that of the Southern Hemisphere being always the inverse sense of rotation to that of the Northern one.

Finally, in the southern seas all the southerly branches of the circulation of the three great oceans, South Pacific, South Atlantic, and Indian Ocean, give a tangential impulsion to the liquid masses, and so thrust them eastwards in a general movement, often accentuated by the anti-trade winds, which in these latitudes are low down and blow also from west to east. The Antarctic Ocean is thus characterised by an exclusively west-east

direction both as regards the movement of the water and by the air which surrounds them.

Thus, there is a great superficial oceanic circulation and also, doubtless, a vertical oceanic circulation maintaining an interchange of water between the warm upper layers of equatorial origin and the deep waters, of polar origin, occupying the great depths. Below 6000 metres [3.75 miles] the temperature of the water at the bottom of the seas is always between 0° C. [32° F.] and 1° C. [33.8° F.].

Even the polar regions themselves, where the sea is covered over with ice-fields, are not exempted from the general law of the circulation of water. The currents traversing these regions displace the ice itself and it was by means of this ice-drift that Nansen, voluntarily imprisoning his ship, was able to effect his journey to the neighbourhood of the North Pole. The mountains of floating ice, the icebergs, which are fragments from the glaciers covering the circumpolar lands, are carried by cold currents even as far south as the regions where transatlantic liners cross. They finally disappear in the warm waters of the Gulf-Stream, after constituting a great danger to navigation in the course of their drift.

The temperature difference between equatorial

waters and the cold waters of the polar regions also causes a flow of water from the Pole to the Equator, because of the resulting difference of density. In that way is produced a superficial oceanic circulation which in magnitude and direction enhances the circulation that is primarily due to the trade winds. There is, thus, a certain relation between the aërial and the marine circulation. We shall see later that this relation is still more direct, and that marine currents, produced by the movement of regular winds, react in turn upon the aërial currents, and produce, by a wonderful interconnection, the general circulation of the atmosphere, even above the continents.

If we look at a map of ocean currents, it is apparent that the general circuits of oceanic circulation lie around the regions of high pressure which exist over the great oceans in the latitudes of 30°. Above these warm currents are masses of air to which the current communicates both part of its heat and part of its movement.

Let us consider in particular the Gulf-Stream; it engenders above it an aërial "Gulf-Stream" which is warm and humid, being rich in water-vapour, since its elevated temperature enables it to contain a greater quantity. When the marine Gulf-Stream meets the continental plateau, and

then the shores of the European continent, it is checked by the obstacle and compelled to alter its route, but the atmospheric stream above it is not so stopped and continues its direction unaltered. The warm and moist air masses constituting it first meet the western shores of Europe and bring to these the warmth which helps to produce their pleasantly temperate climate, and the humidity which leads to their actual rainfall conditions. Always deviated to the right by the Earth's rotation, they condense their vapour over Sweden, Finland, and Russia, the great lakes of which are thus fed, then over the Ural Mountains, and down across the steppes and deserts of Central Asia. The warmth and humidity has been lost in passing over Europe, and it is as dry winds that they pass over Asia in completing their return journey towards the equator. Now when a country is swept by dry winds only, it never rains there, and consequently vegetation cannot flourish. Hence the deserts which mark the route of this atmospheric return current, the desert of Turkestan, the desert of Arabia, and the Sahara Desert. Thus, by a very curious reciprocal effect the Gulf-Stream is indirectly the cause of the desert-forming climates of the Old World.

It also produces many other results. As we

have already said, it produces an atmospheric stream over it which passes on and circulates over the land mass of the Old World. But this air current is subject to the laws which govern all gaseous currents. In particular we know that when a chimney is in draught the pressure is always less great in the interior than outside; there is always more or less of a rarefaction in the central line of an air current, and the rarefaction is greater in proportion as the current is more rapid. Thus, all along the course of the atmospheric stream we observe the rotatory storms, known as cyclones or cyclonic depressions, which constitute the storms of wind and rain which come upon us in Europe nearly always from the westwards. It is for this reason that English sailors have called the Gulf-Stream the father of storms. We thus see what action the marine circulation exerts upon the circulation and the vicissitudes of the atmosphere, even over the continents far away from the sea.

What we have described in the North Atlantic region with regard to the Gulf-Stream applies equally to the North Pacific, with the Kuro-Siwo. This marine current determines the formation of an atmospheric current above its tepid waters, which envelops it and travels with it. Just as

in the case of the Gulf-Stream, its course is in the same sense of rotation as that of the hands of a watch. Similarly also, in the Southern Hemisphere, the three warm currents give rise to three aërial currents travelling above them, both turning in the contrary direction to the hands of a watch.

The consideration of these atmospheric circuits which constitute the general circulation of the atmosphere is due to a French scientist Maurice de Tastes, whose work has been overlooked, and whose name is not even mentioned in certain treatises on meteorology. This conception moreover did not pretend to give details but only a general impression of the atmospheric circulation. The complete theory, which would enable us to predict, with all their most detailed circumstances, every meteorological phenomena without exception, has yet to be attained, but the outline given by Maurice de Tastes will none the less remain as the first exact general representation of the movements with which the air enveloping us is endowed.

What is noteworthy about this result is that it enables us to predict occurrences which formerly were difficult enough to explain after the event, viz.: the cyclones of the tropical regions the pro-

duction of which follows naturally from the conception of aërial current circuits. Let us consider in fact the two aërial currents which carry air along, one above the Gulf-Stream in the North Atlantic, the other above Kuro-Siwo in the North Pacific. These two circuits are separated from each other by Texas and the warm lands of North America. At the period of the summer solstice when the solar temperature attains its maximum, this region becomes heated more rapidly than the neighbouring sea. Consequently, a movement of ascension will be produced in the air strata lying above it and thus it will be the seat of a depression. As a result of this depression, the neighbouring air masses move towards the region and the atmospheric circuits, Atlantic and Pacific, separate up to this point, become displaced, and so come into contact with each other. The molecules of air that, in the region between these two aërial currents, are constrained to rotate in a circle in the opposite direction to the hands of a watch, are forced into the same direction of rotation both by the cyclonic movement due to the local depression and by the rotation couple due to the proximity of the portions of the two circuits travelling in opposite directions. A cyclone is thus produced and the phenomenon occurs each time the con-

ditions which give rise to it recur. Consequently, it is in the warm season and in the regions where the two neighbouring circuits can meet that these rotary storms are engendered. We can, therefore, predict that cyclones will be local and seasonal, and observation verifies this exactly. An admirable confirmation of this theory has been afforded by the absence of cyclones in South America in spite of the proximity of the two circuits of the South Atlantic and the South Pacific, for the reason that between the two the Cordillera of the Andes forms an effective barrier. Cyclones are phenomena which do not attain any great heights in our atmosphere; at 2000 or 3000 metres [1.25 to 2.50 miles], if not quite absent, they are at any rate greatly weakened. Therefore, the Cordillera, the summits of which rise to a height of 6000 and 7000 metres [3.75 to 4.25 miles] and the mean altitude of which in the Argentine region attains and surpasses 3500 metres [2.2 miles] oppose an insurmountable obstacle to the meeting of the Atlantic and the Pacific currents, and, consequently to the formation of cyclones between them.

This double circulation, atmospheric and marine, of which the two manifestations are so directly connected, is completed by a third circulation which is the consequence of the two first, viz.:

the fluvial circulation which returns to the sea the waters that the solar heat has removed from it in the form of vapour, and which atmospheric currents assisted by oceanic currents have transported to colder continents, where it has been precipitated as rain or to high mountains where it has been condensed as snow.

Everyone knows how necessary water is. Where there is none, no animal or vegetable life is found. All the water that is indispensable to the existence of organised beings and indispensable also to that industry which is the accompaniment of life, arises from the condensation of atmospheric water-vapour in the form of rain and snow. If the total quantity of rain falling on the land surface in the course of the year were uniformly distributed, and if the land surface were everywhere quite level and so coincided with a surface concentric with the geoid, the water so falling would, at the end of a year, form a layer 85 centimetres [33.464 in.] in thickness, which implies, considering the area of the continents, an equal quantity of rain occupying a volume of 122,500 cubic kilometres [27,400 cub. miles]. If we recall that the volume of the water of all the oceans is about 1300 million cubic kilometres [312 million cub. miles], it follows that the total annual rainfall

represents about the eleven-thousandth part of this.

Only a portion of this rainfall is restored to the seas by means of rivers. These, in fact, carry annually 28,000 cubic kilometres [6650 cub. miles] of water to the sea, scarcely one quarter of the total water precipitated on the land surface. As regards the rest of the rainfall, part is evaporated, and the remainder absorbed by the ground and by living beings. Rivers actually restore to the oceans only $\frac{1}{48,000,000}$ part of the water that the Sun's heat had raised from them by evaporation. This fraction, viz.: the 28,000 cubic kilometres [6650 cub. miles], is all that, by the double means of the atmospheric circulation and the pluvial circulation, executes a constant circuit between the seas and continents, taking back to the oceanic reserves, by the operation of gravity, the water they lose by evaporation. Rivers thus play in some measure the part in the Earth's economy that blood-vessels do in the living organism, vessels that lead back to its starting-point the blood which has been taken to all parts of the body and which enables it to live.

## CHAPTER XI

### THE ATTACK ON AND DEFENCE OF THE CONTINENTS

IN a figurative sense, the Earth lives, as we have seen. Just as in the case of all living beings, there are possibilities of organic degradation and of alteration or disturbance of function. In the course of the preceding chapter, we have examined the mechanism of the terrestrial circulation; in the present one, we shall see by what agencies the Earth's surface may be attacked and by what means, in a figurative struggle for life, these destructive causes are counteracted.

The gaseous mass which forms the atmosphere, and the liquid mass constituting the oceans, are in perpetual movement around the solid crust that is the external envelope of the Earth's nucleus. This crust, far from being uniform and level, is furrowed and irregular, traversed by valleys and rugged with mountains. We have to consider what happens to this crust in the presence of the

moving fluid masses which unceasingly assail it. In what way, and up to what limit, can the solid material constituting the crust resist the attacks of wind and water? Are there innate means of defence against such incessant activity? We shall endeavour to elucidate this matter in the following chapter.

When masses of air in the equatorial region rise to the upper strata of the atmosphere as a result of the diminution of density caused by the solar heat, they take up with them large quantities of water-vapour, greater in proportion to the elevation of temperature. At 30° C. [86° F.], for example, the maximum pressure of aqueous vapour is measured by 31 millimetres [1.22 in.] of mercury, and consequently represents, in a saturated atmosphere, one twenty-fifth part of the total atmospheric pressure. Carried along with the air by means of the anti-trade winds, this vapour arrives over the cooler countries where these air masses descend down to the Earth's surface. Furthermore, the masses of warm humid air that accompany the oceanic currents and pass on over the continents also bring considerable quantities of water-vapour to the atmosphere of these. As this vapour thus arrives at a region, the temperature of which is lower than that which corresponds

to the pressure of water-vapour actually in the air, some of it rapidly condenses, first in the form of clouds, then rain, and finally snow if the condensation occurs at a sufficiently low temperature, which is always the case on the summits of high mountains. The water so condensed in various forms is the chief agency in the denudation of the land-surface.

The Sun itself, however, begins the action. Under the heating effect of its rays even the hardest rocks become heated during the day. As they are poor conductors of heat, the heating takes place only in the parts directly exposed to the Sun, and consequently the expansion which results from the rise of temperature does not affect the whole mass equally; molecular effects are produced tending to destroy the cohesion which binds the molecules together. Sooner or later, the strain, repeated daily and arrested at night, when there is a corresponding contraction, becomes greater than the molecular cohesion can stand; the rock splits and cracks and instead of a continuous surface the exposed part is fissured and broken.

Then comes the rain. Reversing the Latin proverb, we must here say: *post Phœbium nubila.* The condensed water falls into the crevices and cracks of the rocks. If the rocks occupy an ele-

vated position, for example the top of a mountain, the water does not remain liquid, but freezes in the interstices of the rocks. In freezing, its volume increases, and, thus, with an irresistible force, it widens the fissures and still further separates the walls of rock on either side. This is the second stage of the destructive action; after having been fissured by the Sun's action the rock is subsequently fractured and disintegrated into larger or smaller fragments.

There now supervenes another destructive agency, that of gravity. At the period of formation of those foldings of the crust which were the origin of mountains, the matter composing them was elevated above the mean level of the seas by effects resulting from the more or less recent manifestations of internal energy. These effects, by thus raising the rocky masses and giving them potential energy, for the time being triumphed over the force of gravity; but this reasserts itself as soon as the rocks begin to disintegrate and lose the cohesion which originally bound the whole mass together. The fragments resulting from the action of freezing water fall down the mountains and form a talus of debris at its base. In the descent they frequently knock against each other, and these shocks, absorbing a part of their energy,

end by distributing them in the form of a natural slope from which gravity alone will not suffice to displace them. But, now, a fourth assailant comes into action, viz.: running water derived from the rainfall. Always subject to the action of gravity, water tends to fall to a lower level than that where it originally is. Now solid substances are maintained by friction in more or less steep slopes according to the degree of regularity of the fragments composing the slope. But this is not the case with fluids, which cannot finally remain at rest until they reach a place where the free surface, filling suitable hollows, coincides with a level surface parallel to that of the geoid.

In the course of its descent towards this final level, the water falls with more or less swiftness and vigour according to the steepness of the slopes over which it passes. In proportion as it descends, it takes up and carries along particles that external physical agencies have detached from the land surface; furthermore, in virtue of its force it hollows out a channel which marks its course and so continuously wears away the solid earth. When a drop of water, which represents a liquid projectile, unites with other similar drops the effect of the added mass is multiplied by the square of the velocity. In consequence of this, the stream

that has so taken birth, and which gradually becomes a torrent, eats deeper and deeper into the initial groove in which it flows, and it carries down the material so removed. There are many obstacles in its path however; for example, it may arrive at a hollow or depression in the ground that has no outlet, in which case after transforming this into a lake it has to wear down the edges. Also it may have to fall, in the form of cascades and waterfalls, over any rocks that are too hard to be worn away immediately and so open a passage to its waters. It is only able to wear away such a surface very gradually, but this it does by the constant friction of its waters, aided by the continual knocking of the stones and pieces of rocks previously broken off and carried along by the water.

In all cases, the stream becomes smoother and more gentle little by little; it retains its original impetuosity only among mountains where there are high rocky masses which intercept the waters. In regions of average altitude, and plains, the violence of its descent gradually slackens. The constant friction exercised by the bed of the stream on the water, which always grows larger in volume by the contributions of affluent streams, tends to retard its movement. Also, the slope diminishes

gradually in proportion as the mass of water increases, reducing the velocity and force of the stream. The wearing away of solid matter from the two shores also influences the stream; the rocks, sand, and stones carried along knock against and exert friction on the irregularities of the bottom of the stream and gradually wear them smooth, all the time decreasing the slope of the river in proportion to the distance from the mountains where it had its source—that is, in proportion as it nears the sea.

We thus see that stones, gravel, and sand or, generally, alluvial matter which water has deposited on lands that it covered at a certain period represent, together with mud, the products of destruction of portions of the crust over which a river formerly flowed. But this is not the only way in which running water wears down the relief of the land-surfaces. There is another means, equally effective, which, instead of acting in a continuous manner like the flowing of a stream of water, acts intermittently. This is infiltration. On very inclined slopes, great masses of rock and earth soaked with water may overhang valleys hollowed by the stream. If the layer which supports them is, for example, a clay capable of sliding, the whole mass gives way and

falls down into the valley. In such a way millions of cubic metres [or yards] of debris of all sorts may be thrown down in a few minutes; this is of frequent occurrence in Switzerland.

The tributaries of a river also carry on a similar work of slow and continuous destruction; from the smallest steamlet to the mightiest of rivers every one is producing disintegration of the solid earth over which it flows. The result of this incessant wearing down, prolonged during numerous centuries, should be the complete destruction of all the continents. Under the action of gravity all the materials resulting from their demolition, carried to the seas by running water, would accumulate in the form of sediments at rest on the oceanic bottoms.

We thus arrive at the seeming possibility of a complete levelling of the continental relief by the action of running water, after the elapsing of a sufficiently great length of time. And there is also still another form which the attack upon the solid land by water may take, viz.: the action of glaciers.

On the summits of high mountains rain does not fall: on account of the low temperature, the result of the altitude, the drops of water condense and then solidify, taking a crystalline form and

falling as snow. Snow is very light, because of the numerous spaces separating the branches of its beautiful crystals, and so it is easily driven by the wind, and accumulates in masses which fall as avalanches, carrying down with them stones and pieces of rock detached from the mountains. These consequently fall into the valleys and ravines. The snow also accumulates in these hollows, and under the pressure exerted by the superimposed layers it exhibits the phenomenon of congelation by pressure. It becomes transformed into compact ice, so that a kind of river of ice occupies the bottom of the ravine, a river which slowly descends under the thrust of the upper layers of snow and ice. The velocity is small, of the order of one metre [or yard] daily. Subsequent avalanches fall on to the glacier and deposit large rocks thereon; thus the frozen river or glacier, to give it its proper name, carries along huge blocks that have broken off the mountains from which came the snow that gave rise to it. These blocks become aligned along the edges of the glacier in the form of very characteristic trains which are called moraines. When, at the end of its course, the glacier enters regions of lower altitude or more elevated temperature, so that the ice permanently melts, these rocks are deposited just

beyond its termination where they constitute a kind of embankment or barrier which has received the name of the frontal moraine. This frontal moraine is incessantly traversed by the rapid streams of water produced by the fusion of the ice at the end of the glacier. The constituent rocks are thus rolled one against another when the action of these torrents has, after a time, destroyed their equilibrium and washed out the stones and gravel which supported them in position.

When the glacier is formed of great thickness in the cold regions in the neighbourhood of the poles, its front end may reach down to the sea. There, enormous blocks break from it, and these are carried by ocean currents towards warmer regions. In this way, the icebergs are formed, large masses of ice the sunken part of which is eight or nine times greater than the emergent part. Some icebergs weigh as much as millions of tons. Icebergs may destroy the largest ships, in consequence of their vast size. When they melt completely, any rocky masses that they have torn from the land-surface and have carried with them, fall to the bottom of the sea.

During winters which are characterised by abundant snowfalls, the glacier descends farther, and so encroaches on the valley, while, on the other

hand, after unusually dry years the ice recedes, laying bare the lowest part of its bed. It is then possible to see the destructive action that its descent has produced; it seems as if a gigantic plane had been passed over the ground that was covered by the ice. All the rocks and stones are rounded as if they had been turned, and on their polished surfaces may be seen grooves and scratches produced by the action of small harder stones that the ice has caused to rub against them. Thus, while plains and low valleys are subjected to river erosion, the mountains, in spite of their height and consequently apparent immunity from attack by water, are assailed and disintegrated by the action of snow and ice. Glaciers carry the resulting debris to the end of their course and finally the fragments are subjected to the action of the torrents of water arising from the melting of the ice which finally carry them to still lower regions. Thus, low-lying country becomes covered with the debris of the highest summits. To recapitulate, watercourses constitute a slow but sure agency for the disintegration of the continents, the debris of which they ultimately convey to the sea.

Not only does water wear away the exposed surface of the land over which it flows, but it also has another and more insidious destructive action.

It infiltrates into the mass of the Earth and traverses it in the form of subterranean streams and channels. In the course of this it dissolves a quantity of material from the strata and as finally such water re-enters the ocean, it brings to the latter substances in solution derived from the rocks through which it has flowed. The sea is thus the vast reservoir in which accumulate little by little the materials arising from the demolition of dry land.

It might be thought that there are at any rate certain regions of the Earth's surface immune from destruction by any form of aqueous agency, viz: those where no rain ever falls, in other words the deserts. *Sublatâ causâ, tollitur effectus.*

Unfortunately as regards the relief of such regions, although rain takes no part in their disintegration, the wind plays an equally destructive rôle. The rocks of these regions are subjected to the breaking-up influence of the alternate expansions and contractions caused by the solar heat during the day and the subsequent cooler night. The results of disintegration, fragments of rocks which mutual friction has ground to the condition of grains of sand, are carried by the wind and forced into hollows where they accumulate, or frequently they may be piled up in the

form of dunes. There hard sand grains are flung by the wind against the emergent rocks and so grind them down little by little, producing the curious phenomena of wind erosion so well described by Professor Vélain. Thus, no part of the land surface escapes from the destructive effects of subaërial denudation, which if not due to water, derived from the condensation of atmospheric water vapour, forming rain, watercourses or glaciers, acts through the instrumentality of the winds which, aided by the grains of sand, gradually wear away crags and mountains.

We have just considered the action of water flowing over the Earth's surface, thus forming an immense circulatory system. But the sea is not merely a passive receptacle for the waste of the land brought down to it by running water. The sea also directly attacks the land; raised by the tides, agitated by waves and endowed with a progressive motion by marine currents, it exerts a destructive influence along the shores of the land surface. The force of the liquid masses so projected against rocks and cliffs is enormous and reaches thirty tons per square metre [or yard]. It is estimated that the whole Earth contains about 250,000 kilometres [155,000 miles] of marine shores, so it is obvious that there is a large space

over which the sea's destructive action can be exerted. This action is manifest in the erosion of the hardest granites, as seen on the Brittany coasts, by the rounding of enormous blocks that the waves pile one on the other, by the piercing of great arches, and the falling of whole cliff surfaces, as may be observed on the Normandy coasts. Although very formidable, yet the attack made by the ocean is confined to the region along the shores, while the action of running water is felt over the whole area of an extent of land so that the destructive effect of the latter is eight or nine times greater than that of the sea.

As regards the statistical expression of the work of destruction of the continents, geologists have calculated that the sum total of solid matter yearly removed from the land-surface is about 25 cubic kilometres [6 cub. miles]. We have seen, on the other hand, that the total continental mass elevated above the level of the geoid is about 100 million cubic kilometres [24 million cubic miles]. If the rate of denudation be assumed constant, it would, thus, require four million years to erode the whole of the dry land, and carry to the sea the debris resulting therefrom. The time would actually be less than this, for, in proportion as the solid matter accumulated in the ocean, so would

the level of the latter rise, consequently diminishing the volume of the remaining land. We may, therefore, follow Lapparent in estimating the time necessary for the complete destruction of the continental relief as three and a half million years.

We must now inquire whether the continents have no power of defence against these indefatigable adversaries, and whether they are not able to make some kind of a struggle for life, just as men and all living beings do, instinctively resisting the germs of disease and disintegration.

Such is the case. Since the debris from land destruction accumulates in the sea it is built up in layers on the bottom and so by the slow upward growth of the sediment new strata are added to those which originally formed the solid crust of the terrestrial globe. The way in which this building-up process occurs is simple.

When the sea has sapped a cliff at the base the fragments resulting from its fall become rounded by the action of the waves and so are transformed into shingle. This shingle collects in a line at the foot of the cliff, forming an enbankment which extends parallel to the line of the coast. Beyond the shingle, and washed incessantly by the waves which alternately advance and retreat, are the fine sands and then the ooze which is gradually

deposited at the bottom of the sea, where the violent agitation of the surface is felt less and less in proportion to the depth.

When a large river enters into a tideless sea the water bringing down the sand and mud deposits these materials little by little and the river mouth becomes gradually blocked by the continual arrival of new alluvial matter. A direct passage for the water is all that remains in the midst of the sands so deposited by the rivers. These sands extend seawards more and more, gradually gaining on the sea and forming the characteristic regions that may be seen at the mouths of the Rhone, the Po, the Nile, and Mississippi, and which are called deltas. The vegetable remains carried down by the river accumulate in these deltas. Subsequent deposits bury them under new layers of mud and so protect them from atmospheric action, transforming them into abundant reserves of fuel for future exploitation. If a river enters an ocean that exhibits marked tides, instead of a tideless one such as the Mediterranean or Adriatic, the formation of a delta is difficult, but in such a case a bar is gradually formed by means of the periodical conflict between the river current and the rising tide. A bar is a submarine embankment of mud and sand which

the variations of the tides and the vicissitudes to which the river is subjected may slowly displace, and which always constitutes an obstacle, and sometimes a danger, to navigation on account of its submerged character and the breaking of waves upon it.

The flood-tide adds daily to the bar what is brought down by the river, and the ebb-tide carries the rest of the material into the open sea where it is deposited on the bottom as sand and ooze. Thus, a layer of deposits is formed around the continental coasts, material being laid down over an average breadth of 200 kilometres [124 miles]; near the coasts it is formed of shingle and sand, but farther seawards it is exclusively composed of very fine particles of pure clay which constitutes marine ooze. In this way a sedimentary deposit is slowly built up, gaining more than a millimetre [.039 in.] annually in height.

This describes what occurs along marine shores where important rivers carry down materials arising from the disintegration of solid earth. In the midst of the vast marine expanses which separate the continents from each other, the building up of solid earth occurs by other means. Tiny living creatures work indefatigably at the task of reconstructing new land, finding the necessary

materials for their work in the dissolved mineral matters that the water of the sea has received from the land. They use these substances in the construction of their skeleton or their shell. These microscopic sea-workers are the polyzoa which live in colonies in the tropical seas, when the temperature of these does not fall below 20° C. [68° F.], in the superficial regions of the sea down to a depth of 30 or 40 metres [100 to 130 ft.]. These little beings constituting a veritable vegetation, for their colonies take arborescent forms, construct with the lime extracted from the sea the bases on which they build up their edifice. As this increases in height, the lower portions cease to live, and only the chalk structure remains, the solidity of which increases by reason of the debris accumulated within the interstices of the base as a result of the waves breaking off the emergent branches of the coral. Little by little, the whole is transformed into a coral reef emerging just above the level of the sea at its lowest, and so constituting a great danger to navigation. In front of the north-east of Australia a veritable rampart, a coral barrier, exists.

Often, especially in the Pacific, where the manifestations of internal energy are intense and numerous, submarine eruptions have taken place

which have lifted up volcanic cones to the surface of the sea. These would have been quickly washed away by the agency of the waves, but the polyzoa have gathered round the emergent crater and formed coral girdles or rings, the debris from which, washed off by the sea, accumulated towards the centre and so formed annular islands, the atolls, several of which have become habitable and are actually inhabited by human beings, who thus benefit by the work of these microscopic animals.

Throughout the whole of the sea live animalculæ which are often phosphorescent, and which also extract and solidify the chalky matter that the rivers have dissolved from the land and carried to the oceans. After their death, the chalky envelope of these minute creatures falls to the bottom of the sea in the form of foraminiferal ooze which entirely covers the bottom. Other small animals act similarly with regard to silica, and their debris also adds to the accumulating sediment on the oceanic bottoms.

However, in spite of all, the continents must end by disappearing, for the marine shores become bordered little by little with debris; the level of the sea rises because of the intrusion of solid matter and the surviving parts of the continents always

continue to suffer disintegration by atmospheric agencies while the sea rises higher and higher. Finally, therefore, the continents must completely disappear, all being covered by the water of the sea. Yet there is one way in which this process is retarded, viz: the action of the internal energy manifested as volcanic eruptions and seismic phenomena. We have seen in the course of the preceding chapter that active craters eject an enormous amount of solid matter on to the Earth's crust. That in the Sandwich Islands alone has restored to the crust a quantity of material equal to that which 12,000 years of erosion remove from the land surface. Taking account therefore of the total number of existing volcanoes and also those that have existed in the past we can see they constitute a considerable, if not a complete, compensation for continental diminution due to erosion.

Nevertheless, it must be remembered that the material that is thus ejected above the superficial crust disappears from the central magma whence it comes. Consequently the crust, ceasing to be sustained at every point must sink down and a sinking even to the extent of only a few millimetres [few hundredths of an inch] all over the globe would be a greater loss to the dry land than

the entire gain brought to it by eruptions. We have seen that such sinkings occur, they produce seismic phenomena and earth convulsions. These sinkings may be partially counterbalanced by risings, either sudden or gradual ones, and these always, so to speak, rejuvenate the exterior surface of the crust where they occur, forming new relief, the opposite process to the continual wearing down of the irregularities of the crust by denudation.

# CHAPTER XII

## THE OLD AGE AND DEATH OF THE EARTH

WE have studied the "life" of the Earth: we have pictured its birth and development and have learned something of the continual circulation taking place upon its surface, the electric currents which traverse its mass, and the tremors and shocks to which it is subjected. Finally, we have considered the action of destructive agents upon the land surface and the compensatory influences at work, analogous to those which defend a living being against the attacks of germs of disease. But a healthy being, even if it successfully resist the efforts of morbid action, must finally arrive at a state of old age. With age the natural forces diminish, the circulation slackens and death ensues, an accompaniment of the cold that succeeds the warmth of life.

In these final pages we shall endeavour to find out if the Earth forms any exception to this law, or whether, on the contrary, it also grows old and in due course dies.

In the first place, what is the degree of permanence of the actual present state of the terrestrial globe?

The conflict between the land-surface and the exterior agencies, the latter tending to wear it away and the former striving to defend itself, will endure for a long time yet. The waters will have for many ages to continue their attack against the solid material brought to the surface of the Earth by the play of interior forces, and the changes brought about in the relative position of pre-existing masses by seismic disturbances.

The atmosphere during this time, or at least for some time, will grow richer in carbonic acid. On the one hand, volcanoes, the activity of which seems to be actually increasing and whose manifestations will augment in number in proportion to the foldings of the crust, producing new fissures, set free an abundance of this gas. On the other hand, the immense progress of industry, by utilising to exhaustion the mineral fuel contained in the depths of the Earth's crust, tends to increase the proportion of carbonic acid in the atmosphere.

For some time, perhaps a very long one, this proportion will augment. Accordingly the influence that this gas exerts as regards the conservation of heat will also increase, and this will protect

the Earth against a too rapid cooling. Some idea of this will be obtained by considering that if the carbonic acid actually contained in the atmosphere viz: $\frac{1}{3000}$ part of the atmosphere, were removed, the temperature of the Earth's surface would diminish by 20° C. [36° F.], and this diminution would greatly accentuate the present climatic inequalities of the various regions of the Earth. If, on the contrary, the proportion of carbonic acid were to increase,—for example, if its volume became double,—we should experience a gain of 4° C. [7.2° F.], in temperature, and 8° C. [14.4° F.], if it became quadruple. Furthermore, not only would the mean temperature rise, but there would also be an accompanying tendency to climatic equalisation.

The study of the Earth's past has shown us that variations of this kind formerly occurred, and had an influence upon the phenomena of animal and vegetable life, the importance of which is shown by geology. If the carbonic acid increases, which is shown by the continued absorption by the water of the oceans, above which the proportion of this gas in the atmosphere is one-tenth less than above the land-surface, these conditions of climatic amelioration would be realised, and the following period would be a

temperate epoch, in the course of which there would be no occasion to dread the recurrence of those terrible glacial periods which characterised the beginning of the Quaternary era. The soil would, thus, increase in fertility, for the rise in temperature of the air above it would increase the quantity of water-vapour contained in the atmosphere, and equally, therefore, the abundance of aqueous precipitation. Consequently, there would ensue a richer vegetation and better crops for the use of mankind living in these favoured times.

This, however will only be a temporary alleviation of the Earth's passage towards old age and death. At the end of a considerable number of centuries, estimated by Helmholtz at 17,000,000 years,[1] the Sun will be reduced in size to a quarter of its actual volume on account of the loss of heat due to its continued radiation, and a long time before this has taken place the temperature of the Earth will not exceed zero C. [32° F.]. Life will thus not last for the whole of this period—the great German physicist judged its ultimate duration to be about 6,000,000 years.

What will then happen to the Earth itself after

[1] This calculation was made before the discovery of radioactivity, which, by maintaining the temperature of the Sun and Earth, will largely retard the cooling processes described in this chapter.—*Trans.*

life has ceased to be on its surface? Will Man, by utilising the forces of Nature and the future discoveries of science that will continue to be made, have been able to make use of extra-terrestrial forces and so postpone this state of affairs, or even to betake himself to other and newer worlds?

In the process of the gradual cooling of the Sun and the consequent fall of the terrestrial temperature, the successive stages of the Earth's state after the disappearance of life from its surface will be as follows. The oceans and rivers, will first become transformed into masses of ice, and the clouds having condensed into snow and precipitated on the ground, will no longer afford the Earth the protection they formerly did against loss of heat by radiation into space. From this time, therefore, the temperature will fall with greater rapidity.

Carbonic acid will disappear in its turn; when the temperature is sufficiently low it will fall to the ground in the solid form as a fine snow-like substance, which is nowadays employed in the laboratory to produce cold. This condensation will remove the last defence of the Earth against radiation, and so the rate of cooling from that time on will still further accelerate. When the

temperature reaches 73° C. absolute [200° C. below the ordinary thermometric zero (328° F.)], new oceans will come into being, and will accumulate in the hollows of the ice which covers the planet. These new oceans will be produced by the liquefaction of nitrogen and oxygen and the remaining atmosphere will consist only of hydrogen and helium, and will be in a state of extreme tenuity. The cold crust will thus cover a globe exteriorly inert, but the interior will continue to remain as magma in an incandescent state for thousands of centuries. A very small portion only of this heat will come to the surface, conducted through the crust, which gets thicker and thicker, and the temperature will only be maintained above absolute zero [−273° C. or −459.4° F.] by the radiations received from the cooling sun, which after attaining a dull red condition will also finally become dark.

Then the Sun will enter on its final period, a superficial crust being formed by solidification, just as occurred in the case of the Earth at the beginning of its history. At first it will be a very thin skin, constantly broken and fissured by the force of the internal energy, the interior lavas escaping through it, but, little by little, the solar crust will become continuous.

From that moment its cooling will take place more rapidly proportionally to the relative sizes of the two bodies than that of the Earth at the analogous period of its history for there will be no body at all to supply it with external heat. In a continual darkness, illuminated only by the light of the distant stars, the water-vapour of the solar atmosphere will be precipitated on its surface and form oceans there. Relatively soon after their formation they will become frozen. The gases of the solar atmosphere will condense in their turn and the Sun, also, will then be a globe, whose interior, containing an immense reserve of energy, will be for billions of centuries prevented from cooling by its non-conducting solid crust. The Sun will continue its journey through celestial space, leading with it its cortège of superficially cooled planets, like a great shell charged with a terrible explosive, formed by the endothermic compounds accumulated at its centre and maintained at a temperature of several million degrees.

The Earth also will be in a similar state, but on a much more modest scale, continuing to gravitate around its former Sun with an interior reserve of energy that only awaits a suitable occasion for renewed manifestation, for liberation with the accompaniment of a colossal production of heat.

The collision between two dark bodies in interstellar space appears to be the means whereby the rebirth or rejuvenation of a world takes place. The nearest stars are, however, at so great a distance from us that light, although travelling with a velocity of 300,000 kilometres [186,000 miles] per second takes ten years to traverse it.[1] Therefore, as our Sun is journeying towards the constellation of Hercules with a velocity of 20 kilometres [12.5 miles] per second, at least ten billion years must elapse before this distance can be covered and a collision be actually possible.

But there are not only luminous or living stars in space. We have supposed our Sun extinct and travelling through space. It may encounter a similar body, dark and therefore invisible to us, situated at a less great distance than the stars we see. The chances that such an encounter may occur, increase with the decrease of distance between the two bodies on account of the attraction, which increases in proportion to the square of the diminution of the distance which separates them. The mathematical theory of probabilities has been applied to this subject, and it is found that the probable time elapsing between two

[1] The time is 4.3 years for the star known as the nearest—Alpha Centauri; 8.1 years for the next; 8.7 for the next; 10.1 for the next.—*Ed.*

successive collisions of one body with others in a million million years, is about a hundred times as long as the duration of the life of a sun.

It has been calculated that the meteorites falling on the Sun do so with a velocity of 600 kilometres [362 miles] per second. We may then imagine our two celestial bodies coming together, each possessing a velocity of this kind. The collision will be doubtless oblique for the chances of meeting normally are much smaller. The shock will thus impress on the moving system a movement of rotation, the peripheral velocity of which will be enormous and will attain several hundreds of kilometres [or miles] per second.

Even if the two bodies so colliding were entirely solid, that is to say, if they were cold right through to the centre, the tremendous force of the shock, transformed into heat, would suffice to volatilise completely all the constituent matter. But we know that they may be and probably are great reserves of energy, full of endothermic compounds, the force of which is illustrated by the velocity with which are expelled the jets that actually form the solar prominences. This energy is certainly relatively thousands of times greater than that of our most terrible modern explosives. As to the possibility of such combinations, the continual

disengagement of heat from radioactive substances is a familiar illustration. Endothermic combinations are formed throughout the evolution of suns during their period of brilliancy, and, in all probability, result from the union of hydrogen and helium with carbon and the metals.

When a collision occurs between two extinct suns these substances are decomposed into their ultimate elements, and set free an inconceivably vast quantity of heat.

Then the whole mass is volatilised to give birth to what we call a new star or nova, such for example as Nova Persei. Sometimes perhaps several such bodies might result from the impact, being separated from the original agglomeration of incandescent matter. Two gaseous lateral jets, the result of the obliquity of the impact, will shoot forth forming a spiral, with a velocity of several hundred kilometres [or miles] per second, and the gas composing them will constitute the spiral arms of a new nebula, whose nucleus or nuclei will be stars in process of birth. Thus, there comes into being a nebulous system, with a star in its centre, and all the phases through which our Sun and planets have been will reoccur in the new cycle.

Thus takes place the resurrection of a world.

And, once more, on the great dial of the sky where the life of suns is the measure of minutes, the clock of eternity will have accomplished one of its turns.

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